Design, Organization and Implementation of a Methods Pool and an Application Systematics for Condition Based Maintenance

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Abstract

The everyday increasing competition in industry and the compulsion of faster investment paybacks for complex and expensive machinery, in addition to operational safety, health and environmental requirements, take for granted high availability of the production machinery and high and stable quality of products. These targets are reached only if the machinery is kept in proper working condition by utilizing an appropriate maintenance tactic. In this frame of thought, monitoring of machinery systems has become progressively more important in meeting the rapidly changing maintenance requirements of today's manufacturing systems.

Besides, as the pressure to reduce manning in plants increases, so does the need for additional automation and reduced organizational level maintenance. Augmented automation in manufacturing plants has led to rapid growth in the number of machinery sensors installed. Along with reduced manning, increased operating tempos are requiring maintenance providers to make repairs faster and ensure that equipment operates reliably for longer periods. To deal with these challenges, condition based maintenance (CBM) has been widely employed within industry.

CBM, as a preventive and predictive action, strives to identify incipient faults before they become critical through structural condition assessment derived from Different condition monitoring techniques (CMT) and nondestructive tests (NDT). An effective CBM program requires early recognition of failures and accurate identification of the associated attributes in a feasible manner. The achievement of this proficiency in industry is still intricate and relatively expensive due to deficient information about the potential failures as well as inadequate knowledge or improper application of different CMTs and NDTs.

Accordingly, a new toolbox has been developed to facilitate and sustain effective CBM programs in the automotive supply industry. The CBM toolbox is consisted of three major tools. The first tool is a series of statistical failure analyses which uses the failure history data available in a plant's information system to generate valuable information in tabulated and graphical postures. The second tool is a repository filled with expert knowledge about different CMTs and NDTs formatted in a way that in addition to the concept of each technique, its applicability, detectability, and its pros and cons are expressed. The third tool is an object based problem and cause analysis whose outcome is tabulated problem-cause relationships associated with particular machinery objects. These major tools are also accompanied by two supplementary tools, a financial analysis tool and a selection matrix, to ensure feasibility of all undertaken decisions while using the toolbox.

Zusammenfassung

Zunehmender Wettbewerb in der Industrie erfordert immer kürzere Amortisationszeiten von kapitalintensiven Produktionsanlangen. Wesentliche Voraussetzungen für die Realisierung kurzer Amortisationszeiträume sind eine hohe Verfügbarkeit der Anlagen und das Erreichen einer gleichmäßig hohen und konstanten Produktqualität. Eine effiziente Instandhaltungsstrategie unterstützt diese Anforderungen an die Verfügbarkeit und an die Produktqualität, vor allem durch eine geringe Bedarfswartung und zunehmend vorbeugende Instandhaltungsbemühungen. In der Industrie wird hierzu häufig die zustandsbasierte Instandhaltung (Condition Based Maintenance - CBM) angewendet. Die CBM Methode versucht aus Zustandseinschätzung der Maschinen, abgeleitet von verschiedenen Zustandsüberwachungs-Verfahren (Condition Monitoring Technique - CMT) und zerstörungsfreien Prüfungen (Nondestructive Test - NDT), erste Mängel zu identifizieren, bevor sie sich kritisch auf die Produktion auswirken.

Ein effektives CBM Programm verlangt eine frühe Fehlererkennung und eine genaue Identifikation der Fehlerattribute. Diese Anforderungen werden in der Industrie heute noch unzureichend erfüllt. Die Ursache liegt vor allem in den hohen Kosten, die sich aufgrund unzureichender Information über die potenziellen Fehler ergeben, sowie in der unzulänglichen Kenntnis oder ungeeigneten Anwendung von verschiedenem CMTs und NDTs begründet. Daher werden im Rahmen dieser Arbeit eine neuartige Toolbox und ein Anwendungskonzept entwickelt, um die Umsetzung eines effektiven CBM Programms in der Automobil-Zulieferindustrie zu unterstützen. Hierbei ist der Ansatz so allgemein gewählt, dass er nicht nur auf das Anwendungsgebiet der Automobilindustrie beschränkt ist, sondern auch auf die allgemeine Herstellungs- oder Produktionsindustrie angewendet werden kann.

Die CBM-Toolbox setzt sich aus drei Hauptwerkzeugen zusammen. Das erste Werkzeug fasst statistische Fehler-Analysen zusammen, die die in einem Informationssystem des Betriebes vorhandenen Fehlerdaten auswertet, um die relevanten Informationen tabellarisch bzw. grafisch darzustellen. Das zweite Werkzeug ist eine Wissensdatenbank in der das Expertenwissen über verschiedene CMTs und NDTs verwaltet wird. Dieses Expertenwissen ist so strukturiert, dass zusätzlich zu jeder Methode, ihre Anwendbarkeit, Nachweisbarkeit und Vorteile bzw. Nachteile dargestellt werden. Das dritte Werkzeug ist eine objektbasierte Problem-und-Ursache-Analyse, deren Ergebnis eine tabellarisch dargestellte Problem-Ursache Beziehung von besonderen Maschinenanlagen ist. Diese Hauptwerkzeuge werden durch zwei weitere Werkzeuge, ein Finanzanalyse-Werkzeug und eine Auswahlmatrix ergänzt, die die verschiedenen Entscheidungsmöglichkeiten hinsichtlich der Umsetzbarkeit bewertet.

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List of Abbreviations

AA Automatically Actuated
AAS Atomic Absorption Spectroscopy
AC Alternating Current
ADAD Applicability, Detectability, Advantages and Disadvantages
AES Atomic Emission Spectroscopy
APC Automatic Particle Counters
AT Acoustic Emission Testing
BELT Bubble Emission Leak Testing
CBFA Cause Based Failure Analysis
CBM Condition Based Maintenance
CCD Charge Coupled Detector
CCTV Closed Circuit Television
CE Cost Effectiveness
CMT Condition Monitoring Technique
CR Computed Radiography
CRLT Chemical Reaction Leak Testing
CRT Cathode Ray Tube
CSA Current Signature Analysis
CT Computed Tomography
CTG Capacitance to Ground
CW Continuous Wave
DC Direct Current
DDA Digital Detector Array
DR Digital Radiography
EC Eddy Current
ECT Eddy Current Testing
EI Electrical Inspection
EP Extreme Pressure
ET Electromagnetic Testing
FAAS Flame Atomic Absorption Spectroscopy
FFT Fast Fourier Transform
FR Film Radiography
FTIR Fourier Transform Infrared
GDLT Gas Detection Leak Testing
GS Gas Chromatography
HDLT halogen Diode Leak Testing
HPLC High Performance Liquid Chromatography
HSLT Hydrostatic Leak Testing
ICP Inductively Coupled Plasma
IP Image Plate
IRT Infrared Thermography
LC Liquid Chromatography
LCD Liquid Crystal Display
LDV Laser Doppler Vibrometer
LI Laser Inspection
LMG Laser Microgage
LT leak Testing
MA Manually Actuated
MCC Motor Control Cabinet
MCD Magnetic Chip Detectors
MFL Magnetic Flux Leakage
MS Mass Spectrometry
MT Magnetic Particle Testing
NDT Non-Destructive Test
NMR Nuclear Magnetic Resonance
NR Neutron Radiography
NS Neutron Radioscopy
NT Neutron Tomography
OA Oil Analysis
OBFA Object Based Failure Analysis
OBPCA Object Based Problem and Cause Analysis
OES Optical Emission Spectroscopy
OPC Optical Particle Counter
PBFA Problem Based Failure Analysis
PCLT Pressure Change Leak Testing
PDA Personal Digital Assistant
PEP Post Emulsifiable Penetrant
PLC Programmable Logic Controller
PMC Polymer Matrix Composite
PP Payback Period
PQA Power Quality Analysis
PT Penetrant Testing
RDE Rotary Disk Electrode
RFS Rotrode Filter Spectroscopy
RFS Rotrode Filter Spectroscopy
RILT Radioisotope Leak Testing
ROI Return on Investment
RPVOT Rotary Pressure Vessel Oxidation Test
RSD Relative Standard Deviation
RT Radiographic Testing
RTF Remote Field Testing
RTG Resistance to Ground
SA Stress Wave Analysis
SBFA Station Based Failure Analysis
SEM Scanning Electron Microscope
SFA Statistical Failure Analysis
SPCA Statistical Problem Cause Analysis
SRP Solvent Removable Penetrant
TAN Total Acid Number
TBFA Time Based Failure Analysis
TBMA Time Based Maintenance Analysis
TBN Total Base Number
TFT Thin Film Transistor
TGLT Tracer Gas Leak Testing
TI Thermal Inspection
TOFD Time-of-Flight-Diffraction
TT Tribological Testing
UFECS Usability, Feasibility, Efficacy, Compatibility and Safety
UT Ultrasonic Testing
VA Vibration Analysis
VFD Variable Frequency Drive
VFLT Vacuum Flow Leak Testing
VI Visual/Optical Inspection
WPC Wear Particle Concentration
WWP Water Washable Penetrant
XRF X-Ray Fluorescence

1 Research Context

The everyday increasing competition in industry and the compulsion of faster investment paybacks for complex and expensive machinery, in addition to operational safety, health and environmental requirements, take for granted a high availability of the production machinery and a high and stable quality of the products. These targets are reached only if the machinery is kept in proper working condition by utilizing an appropriate maintenance tactic [37], [38]. In this framework, monitoring of machinery systems has become progressively more important in meeting the rapidly changing maintenance requirements of today's manufacturing systems. Besides, as the pressure to reduce workforce in plants increases, so too does the need for additional automation and reduced organizational level maintenance. Augmented automation in manufacturing plants has led to rapid growth in the number of machinery sensors installed. Along with reduced manning, increased operating tempos are requiring maintenance providers to make repairs faster and ensure that equipment operates reliably for longer periods. To deal with these challenges, condition based maintenance (CBM) has been widely and acceptably employed within industry. Different condition monitoring techniques, nondestructive tests and machine diagnostic methods provide significant support for CBM programs as long as they are properly employed. These include all those evaluation methods by which the integrity of different machinery components or assembled pieces of equipment is being examined nonintrusively.

1.1 General Research Motivation

Overall, maintenance has been the point of interest of different scientific and practical efforts for years. Even so, till the end of the 19th century maintenance had been merely consisted of machinery repair and inspection. In other words, there had been failures and people used to run to them in order to fix the problems. Since the beginning of 20th century maintenance has found its key position in different industries and has been shaped in a more professional way involving different strategies and various tactics in-taking different techniques and technologies. Hence, in twentieth century man has learnt how to deal with failures in the best possible way. However, in the 21st century there exists only an ultimate goal for all maintenance activities and that is to have zero failure. This is not a mathematical zero; it denotes lowering the number of failures day by day, month by month and year by year to reach an optimum situation in which the production system does not suffer from any failure. Nevertheless, reaching the mathematical zero failure would not be a dream in a few decades [325].

Therefore, in a few decades maintenance would have only a preventive role; an essential commitment in which all activities would have either predictive or proactive forms. Such activities entail predicting and anticipating the potential failures before occurrence and working proactively in order to optimize the maintenance activities. This can be the most intelligent and feasible way to prevent failures and the path to the ultimate goal of zero failure. However, converting this frame of thought into a frame of work requires devotion of further conceptual and practical research, outcomes of which will definitely facilitate the industry with valuable knowledge necessary to walk on the right path and arrive at the wanted target [347]. A first step towards enabling such a conversion is to make use of condition-based maintenance, a preventive maintenance tactic which strives to identify incipient faults before they become critical which enables more accurate planning of the preventive maintenance. CBM can be realized by utilizing complex technical systems or by manual monitoring of the machinery condition that is provided by human senses and experience. Although CBM holds a lot of benefits compared to other maintenance tactics it is not still effectively utilized and efficiently used in many companies, a reason of which is employing of CBM without actually being acquainted with it [325].

Condition based maintenance has different aspects and therefore different systems, each of which involves many sub-systems and related issues that can be taken into account for research and development. A CBM process starts with acquiring data from equipment and machinery via transducers and ended with control and command which is based on rich and high-quality information that has been developed through distinct phases of diagnostics, condition monitoring and assessment, and prognostics, see figure 1. The data and information pass through a communication system that feed different sections. Each and every of the CBM system components boasts its weight and importance and can be a taken as a research focus. This decision is to be made based on requirements of a specific case (e.g. characteristics of a particular industry, plant or machinery) or necessities outlined by the stakeholders like a system's weak points identified by an engineer or a technician.

Overview of a CBM System

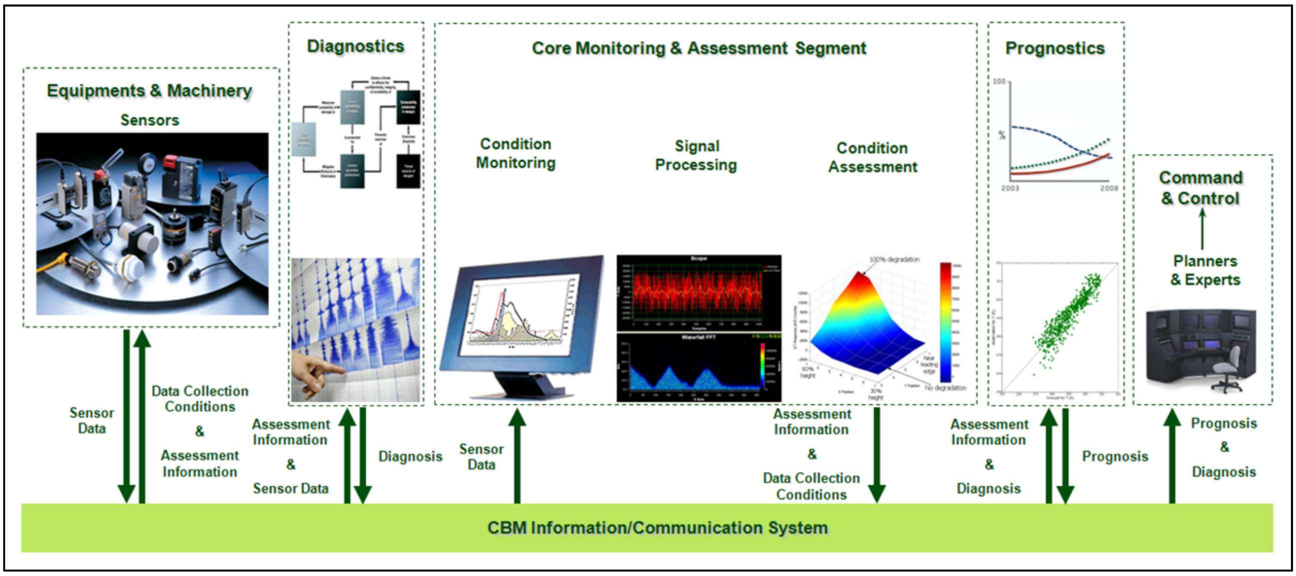


Figure 1 Different components and aspects of a CBM System

Research on any CBM segment will be definitely beneficial for more and better development and improvement of the overall system; eventually, different academic institutes and industrial companies can gain profit from the research results distinctively. However, based on the investigation undertaken by the author and the expert knowledge provided by colleagues and practitioners particularly in the automotive supply industry, it has been reckoned that the dominant barrier against the effective use of a CBM system is not the availability of proper technologies but the readiness of thorough know-what and know-why of various condition monitoring techniques (CMT) and nondestructive tests (NDT) used for CBM. This challenge is then considered to be a major predicament which needs to be dissolved and handled in the most effective and feasible way.

1.2 The Problem and a Potential Solution

Equipment is broken down if it fails to perform its regular function, which is to say there is disruption of normal equipment operation. This expresses that not only when there is function loss but also even if there is a function diminution, it is regarded as equipment failure or breakdown. Equipment stoppage is usually regarded as a major breakdown and not just a disturbance. In the case of function diminution, i.e. function or quality deterioration, continued equipment operation results in production of defective components, reduced output, frequent stoppages, noisy operation, reduced speed, unsafe conditions, and so on. Superior manufacturing companies have for a long time recognized the high costs associated with plant and machinery breakdowns [61]. These costs include inspection, repair, and equipment downtime that are usually measured in terms of reduced productivity, poor quality and increased delivery time [404], [525]. As mentioned above, health and safety is another liability factor and it has to be considered that machinery breakdown must not cause injury [75]. However, as Bengtsson et al. declare, productivity in general is the key factor among all [60].

Generally, a large number of breakdowns occur during startups and shutdowns. However, equipment failure of recently overhauled machine could also be due to poor maintenance. Causes that evade the notice are termed as hidden defects. Thus, the key to reduce breakdowns is to uncover and rectify these hidden defects before breakdown actually occurs. Breakdowns are only a tip of the iceberg. Hidden defects such as sticking, abrasion, looseness, leakage, corrosion, erosion, deformation, scratches, cracks, vibrations, noise, etc., are the irregularities that lie beneath. Even when there are such irregularities, they are neglected because of their minor nature or the perception that such defects are relatively unimportant in comparison with breakdowns. The tendency to overlook such minor defects soon results in minor defects becoming major defects. If these minor defects are not recognized and eliminated as soon as they occur, the initial failure damage may be obscured by subsequent damage and root cause not be known and rectified. Consecutively, this may lead to repetitive or chronic failures. It is, therefore, essential for different companies to employ a reliable CBM program, in which the condition assessment of machinery and equipment is effectively undertaken.

With this incentive, numerous condition monitoring techniques and nondestructive tests have undergone significant advances in recent years. These advances have been manifested by development of new methods or improvement of the available ones. As Dos Reis correctly declares, the driving force behind these activities has been, and continues to be, the need to nonintrusively evaluate and characterize machinery condition as well as to accurately predict fitness for service and remaining useful life of its components or structural system [164]. Like the employment of any new technical concept or technology, its proper application is of critical importance. This need is particularly factual in the field of condition based maintenance that has become increasingly refined and technology-driven. By matching the right CMT/NDT to the proper application, CBM does not need to be extremely complicated, nor does it have to require a large investment of capital.

However, this knowledge does not completely exist in many companies round the globe. Usually, there is trend in the business field based on which companies decide to employ particular CMTs/NDTs, for which they purchase sophisticated instruments and train technicians for proper technical use of them. But then, the missing link is the joint know-what and know-why in application of these tests and techniques. Therefore, there is an essential need to have an extensive overview of all the existing condition monitoring techniques and nondestructive tests, their fitness of use for particular materials and objects (i.e. machinery components), the problems and discontinuity types that can be identified by these CMTs/NDTs, and the advantages and disadvantages of each. With all these information in hand, maintenance managers can reasonably decide what tests are the most appropriate ones for definite applications or certain cases, and thus, establish an effective CBM program.

1.3 Research Proposition, Goal and Stakeholders

Productivity is the armament for manufacturers to keep their competitiveness in today’s turbulent but emergent global market. One of the ways to boost productivity is to increase availability, which can be realized by enhancing maintainability [79]. Maintenance in different superior manufacturing industries like automotive has an exceptional economic significance through the increasing automation and complexity of the manufacturing processes. In view of the extent of the capital bound in equipment and spare parts and the demand for maximum availability there is an urgent need for action. Augmented availability through efficient maintenance can be attained in the course of less corrective and more preventive maintenance efforts. CBM strives to identify incipient faults before they become critical through machinery condition assessment derived from condition monitoring and noninvasive tests. To effectively realize an efficient CBM program, it is necessary to recognize failures at an early stage and to predict the progression of a failure as accurately as possible [107]. Despite modern condition monitoring technologies, the achievement of this goal is still difficult and expensive.

Accordingly, the main objective of the dissertation project is to design and develop a methods pool and an application systematics for different CBM tools that facilitate maintenance department of an automotive supplier with the competency to run its CBM program effectively. This research is based on: analysis of available condition monitoring techniques and nondestructive tests and their associated measured variables, pointing out their fitness for use for specific cases of application and of recommendable methods combinations, evaluation of various CMTs and NDTs regarding to their practical and cost-fair application, the resulting information benefit, and their contribution to the diagnosis and maintenance needs of machinery and equipment. The research work focuses on appropriate use of a blend of suitable analyses which are considered as tools of a toolbox. They provide precious information that can be used to improve the overall maintenance aptitude in a plant and to employ different techniques of condition based maintenance in the most effective way.

It is essential to emphasize that the research approach in building of such a new CBM methods pool is strategically planned to be general. This involves an innovative blend of a variety of CBM related tools and techniques being used in different industries worldwide in addition to the ones under research and development. The methods pool is structured as a novel toolbox that facilitates preventive maintenance efforts not only in the automotive supply industry but also in any other manufacturing or production industry. Its ultimate goal is to enhance CBM management with higher accuracy, reasonability, effectiveness, and efficiency in all decision making processes related to CBM activities. The use and benefit of each individual tool is explained in the corresponding chapters. It is notable that the CBM toolbox can be easily upgraded whenever a tool is remodeled or required to be added.

Stakeholders of this doctoral dissertation are the author of the work, Technische Universität Dortmund, Fraunhofer Institute for Material Flow and Logistics - IML, and TRW Automotive Systems (Schalke, Germany). The research project is structured and authorized by Graduate School of Logistics (former Graduate School of Production Engineering and Logistics) at Technische Universität Dortmund. It is partially supervised by Fraunhofer IML, which provides innovative research, development, engineering and consulting services and tailor-made solutions for companies of all industries. The research project is also partially supervised, and technically and financially supported by TRW Automotive Systems, which is part of TRW's European Steering Operations and manufactures different steering systems for numerous automobile companies such as Audi, BMW, Daimler-Chrysler, Porsche and Volkswagen. Nevertheless, the research content has been intentionally worked out as broad as possible not only to be useful in the automotive supply industry but also in any production and processing industry. This doctoral dissertation also benefits all scholars who carry out research in the field of machinery maintenance and technology management as it covers various scientific issues and provides a concrete foundation for further research and development.

1.4 Dissertation Structure

This dissertation addresses various tools that are gathered and integrated to create the CBM toolbox. After a brief introduction to the research context, **Chapter 1** continues with expressing the general research motivation in the field of condition based maintenance, the current major problem and a potential solution, the research proposition, goal and stakeholders. **Chapter 2** highlights the concepts of systems thinking, and system analysis and synthesis and explains the background behind the undertaken research methodology. **Chapter 3** provides an introduction to the concept of condition based maintenance by reviewing important issues about machinery failure and maintenance and describing the roles and benefits of condition monitoring techniques and nondestructive tests in CBM.

The overture and structure of the developed CBM toolbox are explained in **Chapter 4**. The information flows into, out of and between different tools are also briefly mentioned in this chapter. Besides, the utilization procedure of the CBM toolbox is precisely put in plain words. **Chapter 5** commences the content of the series of statistical failure analyses which all together form the first major tool of the CBM toolbox. These include: time based failure analysis, station based failure analysis, object based failure analysis, problem based failure analysis, cause based failure analysis, statistical problem cause analysis, and time based maintenance analysis.

In **Chapter 6**, the content of the CMT/NDT knowledgebase, the second major tool of the CBM toolbox, is introduced. The knowledgebase contains expert knowledge about the concept, applicability, detectability, advantages and disadvantages of 14 key condition monitoring techniques and nondestructive tests which are employed in different manufacturing and processing industries for the purpose of condition based maintenance. These are namely: acoustic emission testing, electrical inspection, electromagnetic testing, laser inspection, leak testing, magnetic particle testing, penetrant testing, radiographic testing, stress wave analysis, thermal inspection, tribological testing, ultrasonic testing, vibration analysis, and visual/optical inspection.

A financial analysis tool and a CMT/NDT selection matrix are presented in **Chapter 7**. These auxiliary tools of the CBM toolbox standardize and ease the decision making process in choosing the most appropriate CMT/NDT among all possible alternatives. **Chapter 8** renders the concept of object based problem and cause analysis which is considered as the third major tool of the CBM toolbox. This chapter provides the OBPCA undertaken for bearings, compressors, control valves, conveyors, fans, gear systems, and pumps to illustrate the methodic used in such an analysis. **Chapter 9** provides a sample application of the CBM toolbox to illustrate how it can be used in practice. Eventually, **Chapter 10** concludes the undertaken dissertation project underlining some remarks, contributions and future research potentials of the developed CBM toolbox.

2 Research Methodology

The primary objective of any scientific research is to arrive at compelling and legitimate conclusions through scientific enquiry. Valid conclusions can only be reached in an exclusive research that is based on strong scientific foundation if bias can be eliminated. Dunn et al. define bias as a systematic deviation from the truth which can potentially take place in the design, implementation, or analysis of a study [170]. To be able to eliminate or at least minimize the bias, researcher has to gain broad knowledge over the research topic. Another important factor is to have an appropriate research methodology; though, the application of any research methodology without reflection on the underpinning assumptions is flawed. In addition, such a loom is bound to lead the researcher to an incomplete understanding of the situation under consideration, since it places restrictions on the ways he questions the validity of the knowledge unearthed in the application of the methods [96].

For any scientific research, insights from the systems thinking practice are considered useful and supportive in providing a research perspective. The systems thinking approach makes conscious and formal use of the concept of wholeness, as captured in the world system [223]. The concept of a system embodies the idea of a set of elements dynamically related in time [56]. Each of which can affect the performance of the whole; however, none of which can have an independent effect overall [4]. The system exhibits as a single whole with emergent properties which have no meaning in terms of the parts of the whole [28]. In the coming sections, the foundation of the chosen research methodology for this research is scrutinized in more details.

2.1 Nature of Systems

Understanding of the nature of systems is essential for comprehending the emerging way of systems thinking, based on which strategic thinking is formed. Although most people can identify many different systems, few know precisely what a system is. Without such knowledge, one cannot understand them, and without such an understanding, one cannot be aware of their implications in managing scientific, technical and business challenges.

There are many different definitions of “system” in the literature. The one that follows tries to generalize and conclude their core of agreement. A system can be defined as a set of interrelated elements [7]. According to Checkland [122], a systems approach represents a broad view, taking all aspects of a particular problem into account and concentrating on interactions between different parts of the problem. When Weinberg declares that a system is a way of looking at the world, he wants to signify that people view things differently according to each one’s own experience and point of view, and that it is the purpose of the system which gives it its right of existence [657].

Ackoff defines a system as a set of two interrelated elements of any kind; for example, concepts, objects, or people [3]. The system is not indivisible but must be seen as a whole that can be divided into parts. A system is always more than the sum of its parts. A system’s emergent properties are those properties that do not exist in the parts but are found in the whole [657]. A system also forms part of a larger whole or system. The elements of the set and set of elements have the following properties [3]:

- The properties or behavior of each element of the set has an effect on the properties or behavior of the set taken as a whole. For instance, every organ in an animal’s body affects its overall performance or functionality.
- The properties and behavior of each element and the way they affect the whole, depend on the properties and behavior of at least one other element in the set. Therefore, no part has an independent effect on the whole, and each is affected by at least one other part. For example, the behavior of the heart and the effect it has on the body depends on the lungs.
- Every possible subgroup of elements in the set has the first two properties; each has a non-independent effect on the whole. Therefore, the whole cannot be decomposed into independent subsets. A system cannot be subdivided into independent subsystems. To illustrate, all the subsystems in an animal’s body, such as the nervous, respiratory and digestive subsystems interact, and each affects the performance of the whole.

Churchman describes the environment of a system as a part that is outside the system [130]. Ackoff defines the environment of a system as [7]: "A set of elements and their relevant properties, which elements are not parts of the system but a change in any of which can produce a change in the state of the system. Thus a system's environment consists of all variables that can affect its state. External elements that affect irrelevant properties of a system are not part of its environment. The state of a system at a moment of time is the set of relevant properties which that system has at that time". The systems approach considers the system as a whole, consisting of interdependent elements [340]. The specific arrangement of the parts of a system is significant. The environment and the interaction of the system with its environment cannot be ignored.

2.2 Systems Thinking

Systems thinking is the study of objects as wholes and synthesizing all the relevant information regarding an object, in order to have a sense of it as a whole [317]. A system is seen as part of a larger system or whole but also made up of smaller systems. The whole has emergent properties that cannot be found in any of the parts. The specific structures and processes that glue the whole together are responsible for these properties and need to be analyzed. These processes and structures are studied in terms of inputs, outputs, transformations, and interconnections between the components that make up the system [223]. Systems thinking implies a holistic approach to problem solving [317]. A system is a set of interrelated elements. A systems approach represents a broad view, taking all aspects into account and concentrating on interactions between different parts of the problem.

In a practical problem environment, one is quickly reminded of the interdisciplinary holistic nature of the systems approach, when the number of interested parties grows very quickly. The stated objective of the system should be to benefit all the interested parties. However, one should analyze the role players carefully to determine who form part of the environment and who form part of the system's resources. The key is to decide whether the decision maker can determine the conduct of the specific party. If the conduct of the party cannot be determined by the decision maker, the party should be viewed as part of the system's environment. If the decision maker can determine the conduct, the party is part of the resources of the system and should be used to optimize the goal of the system [223].

2.3 System Analysis and Synthesis

The predisposition to take systems apart and to treat the parts separately is a consequence of analytic thinking. Indeed, "analysis" and "thought" are frequently treated as synonyms, but analysis is only one way of thinking and synthesis is another. Both involve three steps, as followings:

- In analysis, something that is required to be understood is first taken apart. In synthesis, the entity to be understood is first identified as a part of one or more larger systems.
- In the second step of analysis, an effort is made to understand the behavior of each part of a system taken separately. In the second step of synthesis, an effort is made to understand the function of the larger system(s) of which the whole is a part.
- In analysis, the understanding of the parts of the system to be explored is then aggregated in an effort to explain the behavior or properties of the whole. In synthesis, the understanding of the larger containing system is then disaggregated to identify the role or function of the system to be explored.

Analysis of a system reveals its structure and how it works. It provides the knowledge required to make it worked efficiently and to repair it when it stops working. Its product is know-how and knowledge, but not understanding. To enable a system to perform effectively, its users must understand it. The users must be able to explain its behavior, and this requires being aware of its functions in the larger systems containing it. Although analysis cannot yield an explanation of the properties or behavior of the whole, it can explain the behavior of the parts by revealing their role or function in the whole [301]. One of the most damaging misconceptions is that problems are objects of direct experience. Conversely, they are abstractions extracted from experience by analysis. Problems are related to experience as atoms are to tables. Tables are experienced directly, not atoms. Human being almost never confronts with separate problems but with situations that consist of complex systems of strongly interacting problems [5].

However, it is a standard practice to reduce major problems to lists of minor problems in order to prioritize and treat them as separate entities. Most people do not generally know how to deal effectively with major problems, with reality taken as a whole. Effective management requires dissolving major problems, not solving or resolving them. Basically, there are four different ways of dealing with major problems: absolution, resolution, solution and dissolution. These can be described as [6]:

1. *Absolution* is to ignore a problem and hope it will take care of itself and go away of its own record. More problems are treated this way than most of the world care to admit. To manage this way is to manage by default. This is attractive to many people because it is much more difficult to attribute responsibility for not doing something that should have been done for doing something that should not have been done. The fact is that letting well enough alone sometimes works well.

2. *Resolution* is to do something that yields an outcome that is good enough or just satisfies. It involves a clinical approach to problems; one that relies heavily on past experience, trial and error, qualitative judgment and so called common sense. It focuses more on the uniqueness of a problem than on what it has in common with the other problems.

3. *Solution* is to do something yields or comes as close as possible to the best possible outcome, something that optimizes. This involves a research approach to problems, one that relies heavily on experimentation, quantitative analysis and uncommon sense. It focuses more on general aspects of problem or mess than its uniqueness.

4. *Dissolution* is to redesign either the entity that has the problem, or its environment, in such a way as to eliminate the problem and enable the system involved to do better in the future than the best it can do today, in a word, to realize. Dissolution focuses equally, on the generality and uniqueness of a problem, and it employs whatever techniques, tools, and methods, clinical or scientific, which can assist in the design process.

2.4 The Methodology

Checkland defines the system concept as [122]: “the idea of a whole entity, which under a range of conditions maintains its identity, provides a way of viewing and interpreting the universe as a hierarchy of such interconnected and interrelated wholes”. This description represents an approach that, unlike the reductionism methodologies, encourages an exploration of the relationships between elements, rather than focusing on the properties of the individual elements themselves, therefore considering performance in terms of the systems structure [544]. Further, there is an implication that systems are governed by the dynamic interactions of their components; a system’s conduct is categorized and analyzed through the patterns of its behavior, or its trends, rather than through seeking to predict events. This systemic perspective encourages closed loop thinking, where it is looking for continuing interrelated processes, rather than one way relationships [5].

The philosophy behind the undertaken research is based on the systems thinking. The overall topic of the research is: “Design, organization and implementation of a methods pool and an application systematics for a condition based maintenance in the automotive supply industry”. However, without understanding the main system, i.e. maintenance, it is not possible to perfectly understand and deal with the subsystems, i.e. condition based maintenance or structuring of an application systematics for it. Hence, there has been an endeavor to understand, analyze and synthesize all the systems involved in, and related to the main theme. Indeed, this needs a greater effort rather than the other research methodologies, but the result will definitely have higher quality as the researcher trains himself as a specialist step by step through each stage of the research.

Moreover, it has been tried not only to solve the given problem but also to provide dissolution. The developed toolbox and application systematics do not only assist maintenance managers, planners and operators with effective tools to identify the most appropriate and feasible methods to solve certain condition based maintenance problems but also facilitate them with continuous redesigning some subsystems (e.g. problem and cause lists in plant’s information system) to eliminate information quality deficiencies, and hence, continuous improvement of the reliability of the provided solutions. As shown, the research methodology is therefore based on the systems thinking to dissolve the given problem.

3 CBM and Condition Monitoring Fundamentals

Higher productivity and cost economy in manufacturing are achieved by operating the production machines efficiently with the least possible downtime. Failure of machine parts is a critical reason for machine downtime and restoration requires spare parts and consumables. Costs of spare parts and downtime reduce the profit margin of the organization and hence, require management's attention [314]. Besides, a considerable fraction of total operating costs in most processing and manufacturing operations can be directly or indirectly attributed to maintenance. These are sufficient motivations for studying any activity that can potentially lower these costs.

Most machinery is required to operate within a relatively close set of limits. These limits, known as operating conditions, are designed to allow for safe operation of machinery and to ensure that equipment or system design specifications are not exceeded. They are usually set to optimize product quality and throughput (load) without overstressing the equipment. Generally speaking, this means that machinery and equipment are operated within a particular range of operating speeds. This definition includes both constant and variable speed machines, which may move within a broader range of operation but still have fixed limits based on design constraints. Occasionally, machinery is required to work outside these limits for short times, i.e. during start-ups, shutdowns and planned overloads [176].

3.1 Machinery Failure

Machinery failure can be defined as the inability of a machine to perform its required function [83]. Failure is always machinery specific. For example, the bearings in a conveyor belt support pulley may be severely damaged or worn, but as long as the bearings are not seized, it has not failed. Other machinery may not tolerate these operating conditions. A computer disk drive may have only a very slight amount of wear or misalignment resulting in noisy operation, which constitutes a failure [506]. There are also other considerations that may dictate that a machine no longer performs adequately. Economic considerations may result in a machine being classified as obsolete and it may then be scheduled for replacement before it has worn out. Safety considerations may also require the replacement of parts in order to ensure the risk of failure is minimized.

When gradual wear on machinery is disregarded as a cause of failure, there are still many specific causes of failure. These are perhaps as numerous as the different types of machines. There are, however, some generic categories that can be listed. Deficiencies in the original design, material or processing, improper assembly, inappropriate maintenance, and excessive operational demands may all cause premature failure. According to the European standard of EN 13306, the failure causes are reasons why they occur, and will be circumstances associated with the design, manufacture, installation, use and/or maintenance of the element. Consequently, there exist design failures, manufacture failures, installation failures, wrong utilization failures and failures which are the result of an inadequate or incorrect maintenance. In this sense, it is central to become aware of the fact that the cause of failure or problem takes in the essential piece of information required to stay away from the failure or recurrence of failures [506].

As with the causes of failure, there are many dissimilar types of failure. Here, these types will be subdivided into only two categories. Catastrophic failures are sudden and complete. Incipient failures are partial and usually gradual. In all but a few instances, there is some advanced warning as to the onset of failure; that is, the vast majority of failures pass through a distinct incipient phase. The goal of machine condition monitoring and fault diagnostics is to detect this onset, diagnose the condition, and trend its progression over time. The time until ultimate failure can then hopefully be better estimated, and this will allow plans to be made to avoid uncalled-for catastrophic repercussions. This, of course, excludes failures caused by unforeseen and uncontrollable outside forces [424].

Getting familiar with the causes of equipment failure is essential for founding an effective course to administer machine health. Claimed by Rabinowicz, internal surface degradation is the cause of 70% of machinery failures and the rest 30% is shared equally by obsolescence and accidence [498]. While there is not much that can be done about obsolescence, something can be undertaken to trim down accidents, and both corrosion and wear can be limited through proper actions.

Corrosion, which is the result of water contamination, degraded oil, contaminated coolant and so on, leads to rust and other forms of oxidation. Abrasion, the largest single category, is caused by dirt in the lubricating oil. Hard particles trapped between moving surfaces become imbedded in the softer surface and then slice grooves out of the harder one. Keeping lubricating oils clean can best control this type of damage. Adhesion, another consequence of inadequate lubrication when the lubricant is unable to support the load, debris is generated and heat is produced along with a lot of ultrasonic sound energy. The fourth major wear mechanism is fatigue, which is directly related to cyclical heavy loads, occurs when cracks propagate under the metal surface and free up chunks and platelets. In fact, ultrasonic signatures can detect and quantify adhesion industry [142]. Figure 2 shows a graphical representation of the mentioned brief review.

Why Equipment Fails

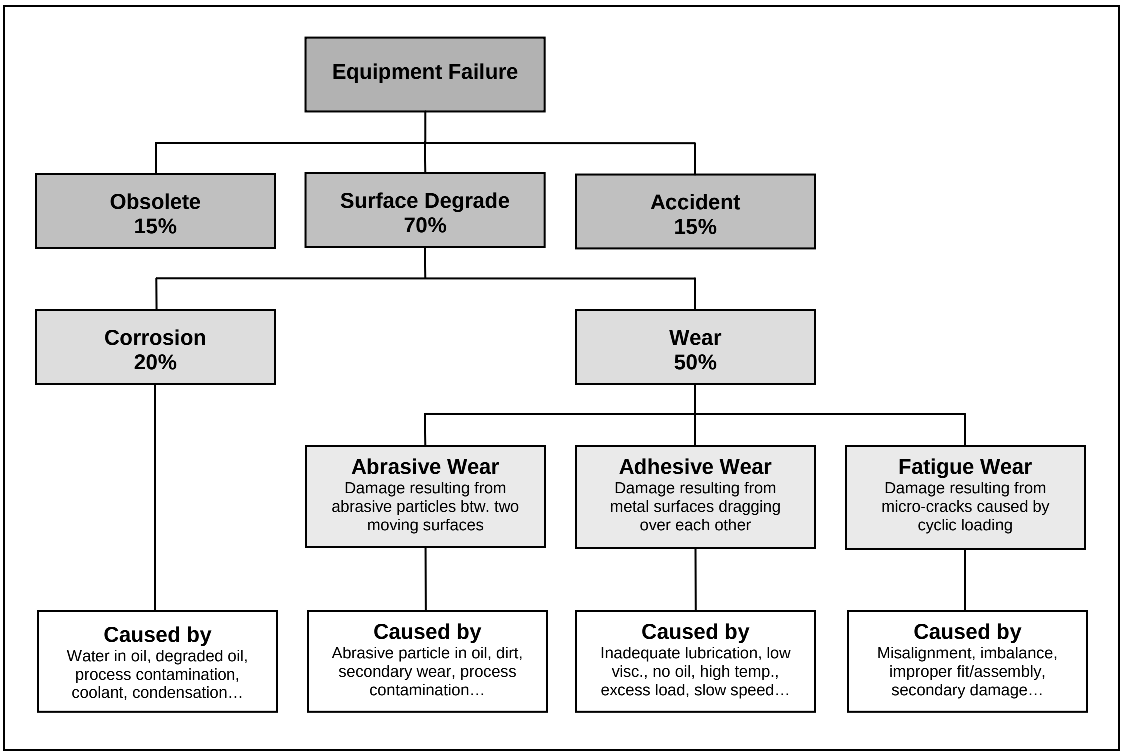


Figure 2 Four most serious wear-related reliability problems in today's industry [142]

Bloch and Geitner claim that various signs, conditions or other indications precede 99% of all mechanical and machinery failures [83]. Mann et al. provide evidences for this claim [404]. Taking this fact into account, various condition monitoring techniques and nondestructive tests have been developed to determine incipient failure [174]. Results of periodic analysis permit scheduling appropriate repairs upon indication of poor machine condition [441], [612]. As Davies expresses, when nondestructive tests are employed in conjunction with one another or condition monitoring techniques, they provide valuable and effective methods to predict machinery and equipment failures [153].

3.2 Machinery Maintenance

Maintenance is a word with which most people are familiar. It is not essential to be an engineer to appreciate that machines fail, and that their failure may be delayed or even avoided by regular maintenance. The 21st century civilization has been built up largely around the application of machines of one sort or another. Thus, everyone can easily understand the concept of maintenance and the consequences which are likely to occur, if it is not conducted correctly and on regular basis, for machines in his care or owner ship [662]. Machinery maintenance receives more and more attention as the high productivity and high capital cost of modern production machines, plus the high maintenance cost of such units dictate such an intensive approach [133]. Maintenance is often regarded as a necessary expense that belongs to operating budget. It is a common item on the hit list of cost reduction programs. With asset availability and reliability becoming critical issues in capital intensive operations, the strategic importance of maintenance in such businesses should be recognized [631].

There are different classifications of maintenance and its types round the world. These classifications are made based on different definitions and interpretations of maintenance terminology and other factors of importance. For example, according to U.S. Department of Energy, past and current maintenance practices in both the private and government sectors would imply that maintenance is the actions associated with equipment repair after it is broken [635]. In literal English, maintenance is defined as the work of keeping something in proper condition, or simply upkeep. This would imply that maintenance should be actions taken to prevent a device or component from failing or to repair normal equipment degradation experienced with the operation of the device to keep it in proper working order. And based on such a definition it catalogs four types of maintenance: reactive, preventive, predictive and reliability centered maintenance [635].

In a European way of explication, maintenance is traditionally performed in either time based with fixed intervals, so called preventive maintenance, or by corrective maintenance. With the preventive approach, maintenance is performed in order to prevent equipment breakdown and do this by performing repair, service or components exchange [280]. With the corrective approach, maintenance is performed after a breakdown or when an obvious fault has occurred, for some equipment the maintenance action must be performed immediately, for others the maintenance action can be deferred in time, all depending on the equipment function [60]; in addition, further information may be obtained by reading the German standard of DIN 31051.

Overview of Different Maintenance Types

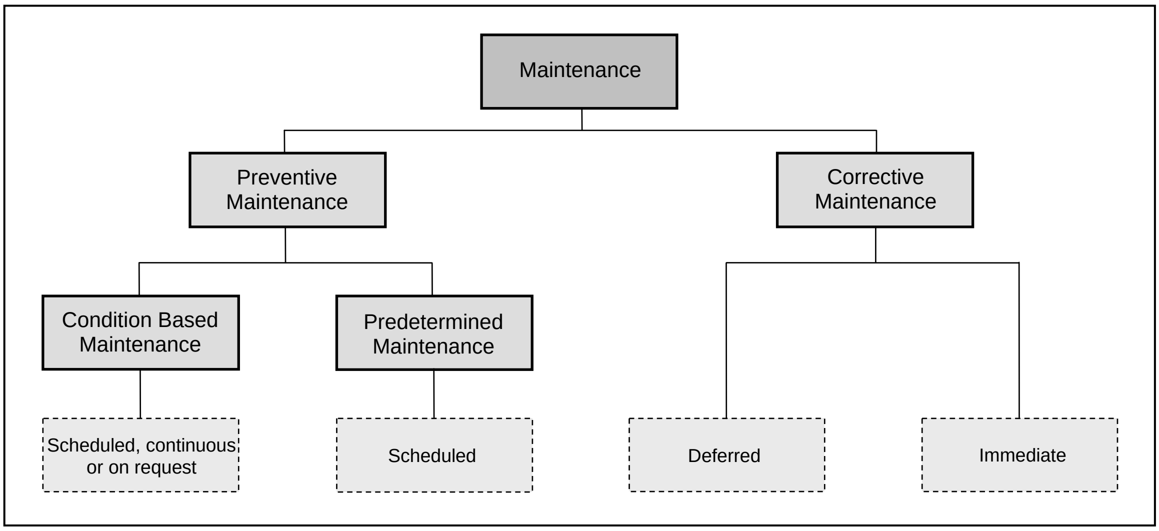


Figure 3 Different maintenance types according to the German/European standard of DIN EN 13306

The principal intention of equipment maintenance is to preserve system functions in a cost effective manner [630]. Within this framework, different parties have their own objectives for maintenance and that is why maintenance performance should be measured from several viewpoints. Therefore, as Tsang underlines, maintenance performance measures can be divided into three common categories: equipment performance, cost performance, and process performance [629]. From the perspective of equipment users, the most imperative goal of maintenance is to minimize the downtime of the equipment. For a maintenance manager, the interests are also in maintenance costs and efficient execution of the maintenance process [366]. The objectives of maintenance can be pursued using different maintenance strategies which all aim at reducing the equipment downtime. These strategies are divided into reactive and preventive maintenance. In the former case, maintenance operations are carried out after an equipment failure has been identified either in a corrective or prospective way, while in the latter category the goal of operations is to replace equipment or return it to good condition before a failure occurs [270]. Preventive maintenance policies can be further divided to planned or predetermined, proactive, and predictive maintenance, which includes condition based maintenance activities [672]. Planned maintenance is carried out when maintenance tasks are performed following a time or usage based schedule [221], [320]. Proactive maintenance is for stabilizing the reliability of machines and reducing the risks associated with possible breakdowns [197]. Predictive maintenance embraces identifying potential failures using condition monitoring techniques and nondestructive tests. A comparison of these maintenance policies and their efficiency is provided in figure 4.

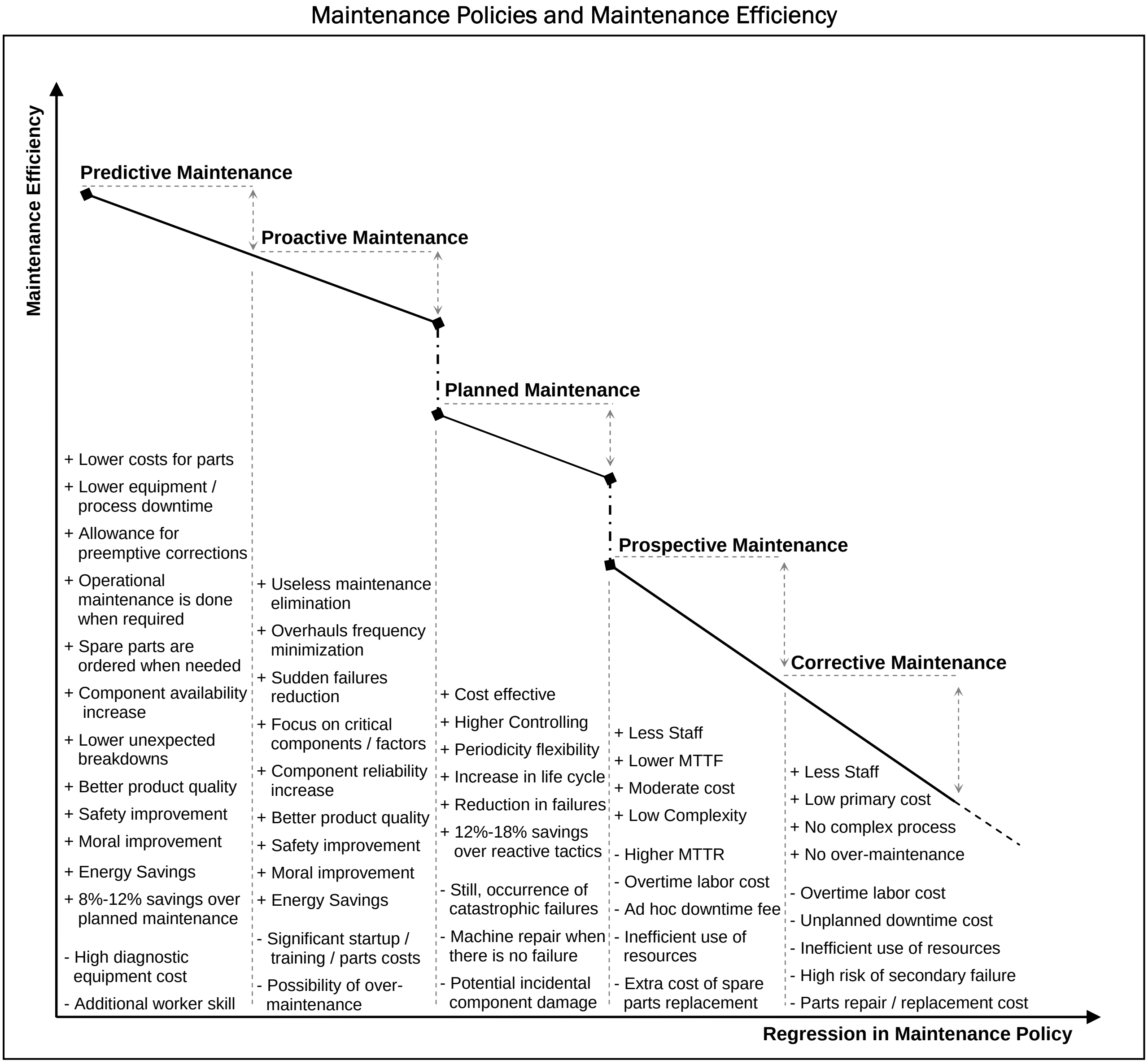


Figure 4 Effect of maintenance policy regression on maintenance efficiency [60], [155], [634]

As a general rule, the most effective way to prevent a component or machinery from failing is appropriate maintenance and frequent inspection of the material for defects and abnormalities. Predictive maintenance lowers the possibility of a material failure due to operating conditions and environmental factors. Nevertheless, it is generally a good idea to develop a maintenance plan before the system is in service. Moreover, routine inspections can sometimes help identifying if an object is at the beginning stages of failure. If inspections are performed in a routine fashion then it is more likely to prevent a component from failing while the system is in service.

The decision to be made about the appropriate maintenance approach and method of implementation is very crucial and depends on a variety of factors. However, the logic behind selection of a proper maintenance policy is not that much complex. As long as there are adequate resources, one can analyze the feasibility of different cases which lead to selection of a right maintenance policy [383]. Figure 5, in the next page, shows how such a decision-making process works. Nonetheless, it is vital to underline that in practice two or more policies are employed in concert; what matters is how they are used [304]. This selection logic does not necessitate elimination of other policies once one is chosen, but rather it portends which maintenance policy has to have more weight for certain machinery or facility. Meanwhile, as long as it is feasible to undertake further hands-on maintenance activities, proactive maintenance should not be neglected and over looked. Within the frame of the selection logic, the word ‘feasible’ means if something is technically, economically and managerially possible and reasonable to be employed to reach a tangible target (e.g. decreasing the failure rate).

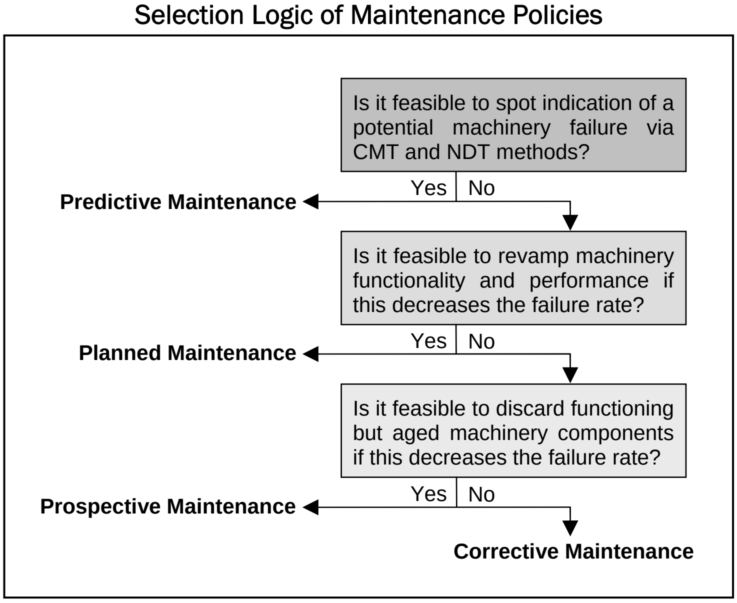


Figure 5 Logic behind selection of different maintenance policies

3.3 Condition Based Maintenance

According to Mitchell in 1998, condition based maintenance is defined as [437]: "maintenance actions based on actual condition obtained from in-situ, noninvasive tests, and operating and condition measurement". Butcher, in the year 2000, delineated the CBM definition as [103]: "a set of maintenance actions based on real-time or near-real time assessment of equipment condition which is obtained from embedded sensors and/or external tests and measurements taken by portable equipment". In the European maintenance terminology standard – EN 13306, published in 2001, CBM has been termed as following: Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. In 2003, Moya and Vera distinguish CBM as [449]: "a program to improve system reliability and availability, product quality, security, best programming of maintenance actions, reduction of direct maintenance costs, reduction of energy consumption, facilitates certification and ensures the verification of the requisites of the standard ISO 9000".

Nevertheless, CBM be considered as a more sophisticated type of preventive maintenance. The condition of the item is monitored continuously or intermittently to carry out preventive maintenance actions only when failure is judged to be imminent. Thus, replacing or servicing equipment prematurely can be avoided. Decision when the maintenance task is carried out is made based on the information obtained via different CMTs and NDTs such as thermal inspection and vibration analysis [630]. CBM assumes that all equipment will deteriorate and that partial or complete loss of function will occur. In CBM, the condition or performance of plant equipment is monitored through various technologies. The data is collected, analyzed, trended, and used to project equipment failures [540]. Once the timing of equipment failure is known, action can be taken to prevent or delay failure. In this way, the reliability of the equipment can remain high. CBM uses various process parameters (e.g. pressure, temperature, vibration, flow) and material samples (e.g. oil and air) to monitor conditions. With these parameters and samples, CBM obtains indications of system and equipment health, performance, integrity and provides information for scheduling correction action [295].

Regardless of the dissimilar definitions of CBM available in different scientific literatures, the common point to be considered is that based on this maintenance tactic, the machinery condition is assessed under operation with the intention of making conclusions to whether it is in need of maintenance or not and if so at what time does the maintenance actions needs to be executed not to suffer a breakdown or malfunction. The degree of automation in assessing the condition can vary from human visual inspection to fully automated systems with sensors, data manipulation, condition monitoring, diagnosis, and prognosis [59], [630], [631]. Employment of CBM tactic results in augmenting the availability of machinery as well as decreasing overall maintenance cost; besides, it raises quality (in general) and improves environmental factors related to production and maintenance.

Comparing physiology to condition based maintenance, one may read the work of Smith that declares that medicine makes complete use of condition monitoring and assessment techniques such as blood pressure and body temperature measuring, examination of body with stethoscope or examination of bones with x-ray [571]. Nevertheless, engineering science has equivalent measures for determining and evaluating the machinery condition; these are named as condition monitoring techniques and nondestructive tests. Each of these tests and techniques can determine the condition of plant, machinery and equipment in a similar way as their medical counterparts [183]. The essential feature of any CMT or NDT is that the test process itself produces no deleterious effects on the plant, material or structure under test. The subject of condition monitoring and nondestructive testing has no clearly-defined boundaries; it ranges from simple techniques such as visual inspection through the well-established methods of thermal inspection, ultrasonic testing and vibration analysis, to the less-known methods of acoustic emission and radiographic testing.

For maintenance purposes, such examinations can be performed directly after manufacturing during acceptance testing or on-line as a condition monitoring tool for failure prediction and prevention as well as failure evaluation and pro-repair inspection. Complementally, the diagnostic methods utilize physical phenomena to monitor the health of the machinery and to make prognosis of the future use and this is often done on-line without interrupting the industrial process. There are many CMTs and NDTs that can be used for condition based maintenance of industrial machinery and equipment. Understanding their applicability, detectability, strengths and weaknesses is critical if the most appropriate technique is to be applied [111]. Of course, understanding how a particular plant item operates is also critical for preventive maintenance. This understanding facilitates preventative measures to be taken when conditions indicating degradation appear, allowing potential problems to be predicted and averted before costly faults and even failures occur.

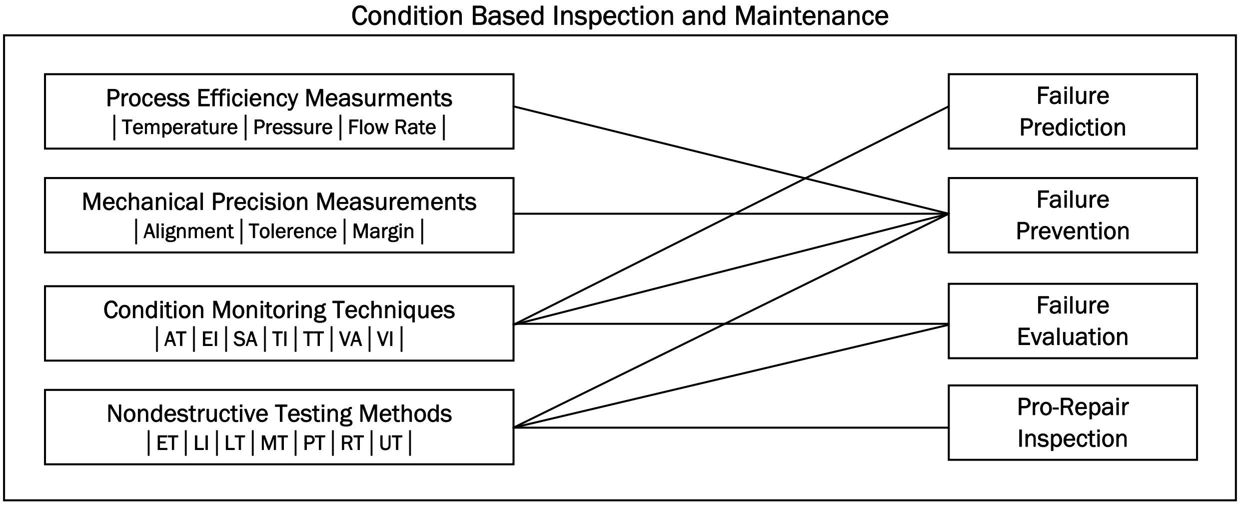


Figure 6 Means of facilitating different courses of condition based inspection and maintenance. The complete names of the condition monitoring techniques and nondestructive tests are provided in the list of abbreviations.

3.3.1 Role of Condition Monitoring Techniques in CBM

Machine condition monitoring and fault diagnostics can be defined as the field of technical activity in which selected physical parameters, associated with machinery operation, are observed for the purpose of determining machinery integrity. Loading and maintenance activities are the two main tasks that link directly to this information. The ultimate goal in regard to maintenance activities is to schedule only what is needed at a time, which results in optimum use of resources. It should also be noted that condition monitoring and fault diagnostic practices are also applied to improve end product quality control and as such can also be considered as process monitoring tools [155]. There are different techniques that facilitate achieving a precise machinery condition evaluation. Problems and defects of all kinds arise in the development and use of mechanical devices, electrical equipment, hydraulic systems, transportation mechanisms and the like. However, an extremely wide range of methods and techniques are available to assist examining these different problems in various materials and machinery under varying circumstances. It is essential to select the most suitable technique for equipment monitoring in a certain case.

The main reason for employing machine condition monitoring and fault diagnostics is to generate accurate, quantitative information on the present condition of the machinery. This enables more confident and realistic expectations regarding machine performance. With condition monitoring, any deterioration in machine condition can be detected and preventive measures can be taken at a right time to avoid catastrophic failures. This is achieved by monitoring such parameters as vibration, wear debris in oil, and acoustic emissions. The changes in these parameters help identifying the development of faults, diagnosis of problem-causes and anticipation of failure. Having such reliable information allows for the following questions to be answered with confidence [155]:

- What is the expected failure mode?
- What is the expected time to failure?
- Will a machine stand a required overload?
- What maintenance activities (if any) are required?
- Should equipment be removed from service for maintenance now or later?

The eventual goal of machine condition monitoring is to provide useful information on the condition of equipment to the people who need it in a timely manner. The task of the person or group in charge of condition monitoring and diagnostics is to ensure that useful data is collected, that data is changed into information in a form required by and useful to others, and that the information is provided to the people who need it when they need it. The types of information that can be gleaned from the condition monitoring data include: existing condition, trends, expected time to failure at a given load, type of fault existing or developing, and type of fault that caused a failure [392], [436]. Maintenance and/or corrective actions can be planned accordingly. The application of condition monitoring in plants results in savings in maintenance costs, and improved availability and safety [650]. The merits and demerits of condition monitoring can be listed in the following table:

Table 1 Merits and demerits of condition monitoring [155]

Condition Monitoring	
Merit	Demerit
Better machine reliability	Operational costs
Improved safety condition	Require skilled personnel
Better machine availability	Require strong management involvement
Superior risk management	Inspection and monitoring equipment costs
Abridged maintenance costs	Long run-in time to collect data histories and trends
Elimination of chronic failures	-
Improved operating efficiency	-
Bargained spare parts inventory	-
Extended machinery operational life	-
Reduction of secondary maintenance failures	-
Superior knowledge about machinery condition	-
Better customer relations due to less downtime	-

The specific tasks which must be undertaken to complete a successful condition monitoring program include detection, diagnosis, prognosis, postmortem, and prescription. Detection requires data gathering, comparison to standards, comparison to limits set in-plant for specific equipment, and trending over time. Diagnosis involves recognizing the types of fault developing (different fault types may be more or less serious and require different action) and determining the severity of given faults once detected and diagnosed. Prognosis, which is a very challenging task, involves estimating (forecasting) the expected time to failure, trending the condition of the equipment being monitored, and planning the appropriate maintenance timing. Postmortem is the investigation of root-cause failure analysis, and usually involves some research-type investigation in the laboratory and/or in the field, as well as modeling of the system. Prescription is an activity that is dictated by the information collected and may be applied at any stage of the condition monitoring and diagnostic work. It may involve recommendations for altering the operating conditions, altering the monitoring, or redesigning the process or equipment. The tasks listed above have relatively crisp definitions, but there is still considerable room for adjustment within any condition monitoring program. There are always questions, concerning such things as how much data to collect and time to spend on data analysis [448], [504].

3.3.2 Role of Nondestructive Tests in CBM

Nondestructive tests are noninvasive methods to determine the integrity of a material, component or structure or quantitatively measure some characteristic of an object. In contrast to destructive testing, an NDT is an assessment without doing harm, stress or destroying the test object. The destruction of the test object usually makes destructive testing more costly and it is also inappropriate in many circumstances. Within the context of condition based maintenance, NDTs are used to identify and quantify damage to a component [558]. These tests can be employed extensively to gain knowledge of any change in materials' physical conditions from an established baseline or a rate of change. This can be done on a routine or one-time basis, depending on the circumstances. NDTs can provide insight into condition of an operating system, with the aim to identify deteriorating components before they fail.

Nondestructive testing is considered to be an essential element of condition based maintenance programs to manage plants' physical assets for higher availability of equipment and lower maintenance expenses [563]. Integration of NDTs in CBM is aimed not only to maximize but also to optimize the effectiveness of inspection and trouncing deficiencies of planned maintenance activities. In fact, nondestructive testing plays a crucial role in ensuring cost effective operation, safety, reliability and maintenance of plant. NDTs are used in a wide range of industrial areas and employed at almost any stage life cycle of many machinery components. Nevertheless, for implementation of any NDT it is important to exactly describe what shall be found at what degree of sensitivity or accuracy. For this reason testing specifications are indispensable. Nowadays there exist a great number of standards and acceptance regulations. They describe the limit between good and bad conditions, but also often which specific NDT method has to be used [284].

On the other hand, the reliability of an NDT Method is an essential issue as well. But a comparison of methods is only significant if it is referring to the same task. Each NDT has its own set of advantages and disadvantages and, therefore, some are better suited than others for a particular application. Indeed, the effectiveness of any particular NDT depends upon the skill, experience, and training of the person(s) performing the inspection and testing process. Each process is limited in its usefulness by its adaptability to the particular component to be analyzed. The type of component and nature of possible failures generally specify the particular nondestructive test and procedure to be used [284].

To get acquainted with potential benefits of nondestructive tests, one can consider the following case: when NDT related data on flaw or crack size is combined with information on material properties, the operating environment, and flaw initiation and growth rates, a fracture mechanic specialist can calculate a probability of failure for the component. Moreover, this information can be converted into a remaining life estimate, if the future operating pattern can be supplied. The probability of failure can then be used to make run/repair/replace decision for that component based on the predicted cost of failure [615]. In addition, Nondestructive testing can be a significant contributor in the decision-making process to increase the load or extend the lifecycle of a component.

Frequent monitoring of the equipment for a suitable period of time could produce indications whether or not the operating conditions had been placed too near the failure line. With this data in hand, there may be sufficient economic justification for increasing the load or extending the life of machinery, provided that it can be done without catastrophic consequences. Conversion of the results from NDTs to remaining service life prediction is another area requiring development for successful implementation CBM programs. This may require consideration of failure mechanisms, kinetic and probabilistic aspects of equipment failures. Nonetheless, combination of nondestructive tests with on-line condition monitoring techniques provides additional information on component performance.

Nondestructive testing methods already have wide application in maintenance of production and manufacturing facilities. Being an essential part of any predictive maintenance program [231], NDTs can also be beneficial in reducing the frequency of unscheduled maintenance, which is usually more expensive than planned maintenance [64]. Additionally, planned maintenance periods may be kept longer with the proper use of NDTs in plant. Knowing from a noninvasive inspection that crucial parts are not approaching failure may allow the machinery to be operated safely for a longer period of time [93]. Less frequent planned maintenance may be cost-effective provided that the cost of operation is not increased due to an unexpected failure.

3.3.3 Metering Methods in CBM

Once a company uses a maintenance tactic which is centered on machine diagnostics, the problem of inspections arises. The basic economic choice is to decide between a continuous monitoring and a periodic inspection and to investigate the merits of both policies considering the main direct costs involved [527]. Turco and Parolini proposed a mathematical model of on-condition maintenance; the model determines an almost optimal string of inspection times which provide the lowest maintenance intervention and inspection cost per time unit [633].

As De Silva states periodic inspection entails intermittent data gathering and analysis with portable, removable inspection equipment [155]. From time to time, permanent monitoring hardware may be used for periodic inspection, but data is only collected at specific times. Periodic inspection is usually applied to uncritical equipment or machinery where failure modes are well known, i.e. historically reliable equipment. Trending of condition and severity level checks are the major spotlights.

Continuous or recurrent data gathering, compilation and analysis is referred to as continuous monitoring. Permanently installed monitoring systems are typically used, with automatic sampling and analysis of data. Continuous monitoring is carried out on critical equipment and machinery that are indeed expensive to replace, with costly downtime and related lost production [592]. Changes in condition trigger more detailed investigation or possibly an automatic equipment shutdown [155]. Regardless from the fact if a preventive maintenance activity is based on period inspection or continuous monitoring there are different metering policies which can administer the data measurement in such an activity. It is possible to classify metering policies into four different groups with unique characteristics: one time measurement, run-time measurement, short-term measurement, and long-term measurement. These metering policies are described in the followings [178]:

- **One-Time Measurement:** This metering policy, also known as Spot Measurement, is useful in many activities to understand instantaneous energy use, equipment performance, or equipment loading. These measurements become particularly useful in trending equipment performance over time. There is large variety of equipment useful in making spot measurements for example, clamp-on probes, contact and non-contact temperature devices, non-intrusive flow measurement devices, and different combustion-efficiency devices. Most of these measurements are obtained and recorded in the field by an analyst.

Table 2 Merits and demerits of one-time measurement [178], [192]

One-Time Measurement	
Merit	Demerit
Ease of use	Low accuracy
Fast results	Limited application
Lowest cost	Measures single operating parameter
Non-intrusive	Measurement at a single point in time

- **Run-Time Measurement:** These measurements are made in situations where hours-of-operation are the critical variable. Appropriate applications for run-time measurements include the run times of fans and pumps, or the operational characteristics of heating, cooling, or lighting systems. Equipment useful in making run-time measurements include a variety of stand-alone data loggers providing time-series record on run-time. Most of these devices are nonintrusive (i.e. the process or system is not impacted by their use or set-up) and are either optically triggered or take advantage of the electromagnetic characteristics of electrical devices. Run-time measurements are usually obtained in the field by a handheld device, recorded to memory, and then downloaded into a computer at a later date.

Table 3 Merits and demerits of run-time measurement [178], [192]

Run-Time Measurement	
Merit	Demerit
Low cost	Limited application
Non-intrusive	Measures single operating parameter
Relative ease of use	Requires additional calculations/assumptions
Useful for constant-load devices	Requires recovery and/or manual data download

- **Short-Term Measurement:** It combines both elements of the previous two policies into a time-series record of data: magnitude and duration. Typically, short-term monitoring is used to verify condition or performance, initiate trending, or validate utility efficiency improvement. In this policy, the term of the monitoring is usually less than one year, and in most cases on the order of weeks to months. Devices useful in short-term monitoring include a host of portable, stand-alone data loggers capable of multivariate time-series data collection and storage. Most of these data loggers accept a host of sensors including temperature, pressure, voltage, current flow, etc., and have standardized I/O communications. These loggers are capable of recording at user-selected intervals from fractions of a second to hourly to daily recordings. These systems usually rely on infield manual downloading or, if available, local network connections.

Table 4 Merits and demerits of short-term measurement [178], [192]

Short-Term Measurement	
Merit	Demerit
Middle-level cost	Mid-level accuracy
Relatively fast results	Limited application
Can quantify magnitude and duration	More difficult to undertake/monitor
Data can be recovered remotely over data lines	Seasonal or occupancy variance deficient

- **Long-Term Measurement:** This policy also makes use of time-series recording of data, but over a longer duration. Different from short-term use, it focuses on measurements used in long-term condition, trending or performance verification. The term is typically more than a year and quite often the installation is permanent. Useful applications for this type of monitoring include situations where system use is influenced by different variances. Equipment useful in long-term monitoring includes a variety of data loggers, utility-grade meters, or fixed data acquisition systems. In most cases, these systems communicate via a network connection to a host computer and/or over the Internet.

Table 5 Merits and demerits of short-term measurement [178], [192]

Long-Term Measurement	
Merit	Demerit
Highest accuracy	High Cost
Captures most variance	Time duration for result availability
Can quantify magnitude and duration	Most difficult to undertake/monitor
Data can be recovered remotely over data lines	-

3.3.4 CMT/NDT Qualitative Benefits

The value of an efficient condition based maintenance program, and hence, effective condition monitoring and nondestructive testing of machinery and equipment in manufacturing and processing plants may seem to be intuitively clear. However, many of the tangible and intangible benefits of acquiring and utilizing CMT/NDT systems are often extremely difficult to quantify in monetary terms. Many scholars and practitioners like Davies [152], Jones [308] and Rao [504], and some scientific and technical institutes like Institute of Electrical and Electronic Engineers, IEEE, [294] have expressed some of these benefits. These qualitative benefits can be summarized and described as:

- **Minimized inspection disruption** - There are many periodic inspections taken place to allow for more detailed observation of plant machinery and equipment. The utilization of an effective CMT/NDT system can reduce or eliminate the need for these disruptions as the system has the potential to deliver a better indication of overall machinery or equipment condition with less frequent need for such inspection disruptions. Benefits will result from not only saving the direct cost of the disruptions but also from not experiencing the associated loss of revenue due to the production loss. Besides, an intangible benefit is the reduction of risk associated with diminishing machine exposure during inspections to accidental intrusion of foreign objects capable of causing consequent damage.

- **Efficient planned maintenance** - When a production or process facility is stopped for planned maintenance, a significant portion of the time-scheduled and calendar-driven maintenance work can be discerned to be unnecessary. An effective CMT/NDT system, enabling condition based maintenance, has the potential to reduce planned maintenance frequency by helping to ensure that maintenance work is only executed whenever it is really necessary.

- **Minimized repair time** - Just as an effective CMT/NDT system can be utilized to lower planned maintenance frequency, likewise when such maintenance activities are necessary the system has the potential to reduce overall repair time. By utilizing the CMT/NDT system to verify the actual condition of plant machinery and equipment, problems can be precisely identified, maintenance work can be effectively scheduled and repair parts can be made available prior to actual repair.

- **Decreased failure frequency** - The information provided by a comprehensive CMT/NDT system of a plant will allow operations and maintenance staff to make more informed decisions concerning plant machinery and equipment. By using this information to trend and predict potential machinery problems, many times minor corrective actions can be performed before the problem becomes severe and thereby eliminating a potential major failure.

- **Reduced maintenance hours** - All of the formerly mentioned optimizations will eventually result in reduced staff-hours for maintenance of the machinery and equipment which are being tested or monitored. This can cause reduced overtime costs or, in some cases, ensue actual reduction in the number of maintenance staff. Either way substantial savings can be achieved.

- **Improved operational and maintenance skills** - Information provided by an effective and comprehensive CMT/NDT system of a plant can be utilized by operations and maintenance staff to make more informed decisions on plant machinery and equipment. Operations staff can exploit the information to maximize the output of the equipment under all conditions without putting the machinery health at risk. Maintenance staff can also exploit the information to make more intelligent decisions about the health of the machinery and equipment and carry out minor corrective actions prior to their deterioration.

- **Increased machinery operating efficiency** - Information provided by an effective and comprehensive CMT/NDT system of a plant can facilitate operations staff with maximizing the operating efficiency of the production or processing machinery. By comparing the actual output and energy consumption of the facility with theoretical optimum values, the operations staff can adjust production or processing facility output maximizing its efficiency.

- **Increased production or processing capacity** - Some potential exists for CMT/NDT system to enable scheduled overloading of production or processing facilities. The information available from facilities which are being tested or monitored can be employed to guarantee minimal impact on machinery life and maintenance costs plus augmenting the overall system peak capacity, thus, avoiding the incremental cost of acquiring new production or processing capacity.

- **Enhanced equipment safety** - The information provided by CMT/NDT system can be utilized to operate plant machinery and equipment as safe as possible while grasping all potential capacity of the equipment. Advance prediction of degraded machinery condition will allow operation staff to run the machinery for longer intervals without risking its health or safety.

- **Enhanced personnel safety** - By allowing the plant machinery and equipment to be operated as safe as possible, plant CMT/NDT system can diminish the hazard to operating and maintenance staff from catastrophic failures.

- **Reduced spare parts inventories** - By installing and utilizing an effective CMT/NDT system, operators can minimize the need for spare parts inventory. Nondestructive testing and condition monitoring of plant machinery equipment facilitate maintenance staff with prediction of potential or imminent machinery problems in advance and allow additional time to locate spare and replacement parts prior to necessary planned or corrective maintenance actions.

- **Rising plant life expectancy** - The major benefit and ultimate goal of a plant CMT/NDT system is the eventual extension of plant's life. Many of the benefits mentioned before all lead toward this goal. Such a system will allow for operation of plant machinery and equipment in areas where wear is abridged thereby extending life. Furthermore, operations and maintenance staff can monitor plant machinery and equipment for signs of deterioration and take minor corrective actions if required; this can delay or eliminate major overhauls and rehabilitations in the future.

- Remote machinery operation - In recent years with advancement of automation technologies, many plants have been looking to reduce operating costs by installing new control systems which allow remote operation of the production or processing facilities. The use of an effective and comprehensive CMT/NDT system have the potential to yield significant benefits and allow safer operation by providing remote operations staff with up-to-date or even real time assessment of machinery and equipment condition. The information provided by the CMT/NDT system can either be presented to remote operating staff for interpretation or it can be presented as recommendations for operational restrictions by the use of expert systems.

3.4 Towards Establishing CBM Programs

Ever since people realized the fallibility of mankind and, hence, his machines, they have acknowledged a necessity to inspect these machines with the aim of preventing failures through proper maintenance. Preventive maintenance attempts to detect the inception of a degradation mechanism with the goal of correcting that degradation prior to significant deterioration in the component or equipment. The decision to launch a predictive maintenance program is the first step to control maintenance costs and improve process efficiency in production and processing plants. Various predictive maintenance tactics can serve as models for implementing a successful predictive maintenance program [442]. Among these, condition based maintenance with recent advancements in diagnosis technologies is a considerable alternative. In general, condition based maintenance necessitates use of some tools for assessing operating condition of the machinery to facilitate an optimally scheduled maintenance, in order to attain very high productivity, and still avoid unexpected catastrophic failures. Condition based maintenance should be employed when the following circumstances exist [155], [440]:

- Hazardous potential failures
- Expensive equipment overhaul
- Remote or mobile equipment or machinery
- Equipment repair needs highly trained people
- Expensive or critical equipment and machinery
- Feasible machine condition monitoring program
- Lack of highly skilled maintenance crew in number
- Long lead-time for replacement of machinery components
- Uninterruptible process, i.e. disturbances are excessively costly
- Costly possible secondary damage(s) due to corrective maintenance
- Failures are not indicated by degeneration of normal operating response

Condition Based Maintenance, despite of its need for high-tech monitoring equipment and techniques, and trained specialist which are considered to increase the related costs, brings lots of merits which can be listed as follows [114], [442], [538], [643], [673]:

- Cutting overtime costs
- Increasing overall profits
- Improving process efficiency
- Enlarging production capacity
- Increasing machinery availability
- Optimizing spare parts inventory
- Decreasing production downtime
- Reducing overall maintenance costs
- Eliminating unnecessary maintenance
- Detecting potential major failures before occurrence
- Reducing secondary failures due to reactive maintenance
- Extending operating life of plant equipment and machinery
- Increasing safety factors of plant equipment and machinery
- Avoiding untimely replacement of equipment and machinery components
- Increasing efficient use of all maintenance resources, e.g. technicians and spare parts
- Reducing product rejects, reworks and scraps due to higher overall machinery condition
- Improving maintenance activities due to higher availability of spare parts and technicians

One of the major benefits of an effective CBM program is optimization of the time required for defect rectification or treatment through precise machinery condition assessment and availability of spare parts and maintenance personnel. Based on the study conducted by Knotts [335], and Lehtonen and Ala-Risku [366], the time it takes to rectify a defect consists of the following four main phases: identification that a problem exists, gaining access to the equipment, diagnosing the problem and locating the cause, and taking necessary corrective action. Knotts argues that there are differences in the predictability for the durations of the different steps of defect rectification time [335]. He explains that time covering access, defect rectification, and test and close up can be predicted based on either experience or predictive techniques. Quite the opposite, the problem identification and fault diagnosis times are difficult to forecast. Nevertheless, with use of advanced techniques and technologies integrated in condition based maintenance, the time required for problem identification and fault diagnosis can be considerably reduced. Plus, the problem identification can take place quite in advance allowing for early and efficient planning of all resources required to be available for further stages of defect rectification. This is how, condition based maintenance fruitfully differentiates itself from corrective or planned maintenance conducts.

Components of Defect Rectification Time

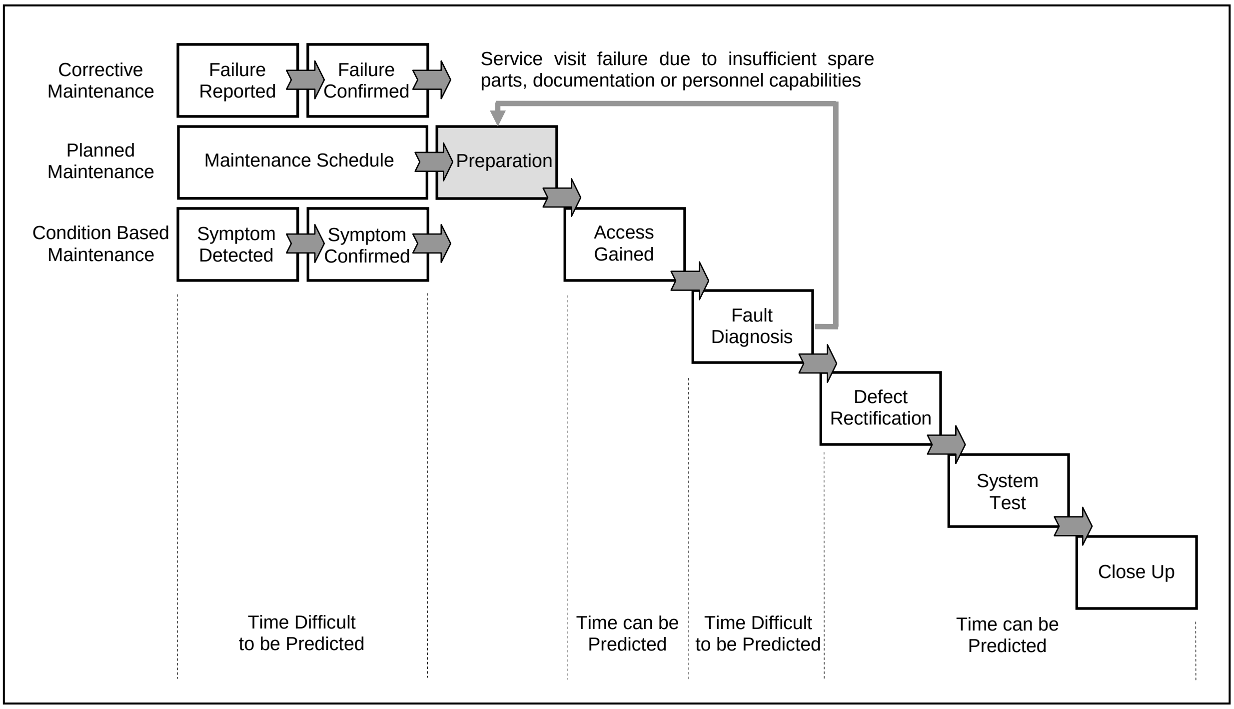


Figure 7 Major steps in fault rectification and its related time prediction characteristics [335], [366]

The procedure in the above figure is triggered by identification of an existing or potential problem. For machinery run under corrective maintenance strategy, the problems are identified after a failure occurs and the downtime timer is started ticking. This does not hold for preventive maintenance in which the problem identification is carried out using CMTs/NDTs while the equipment is operational or during planned stoppages. Thus, the time required for identification does not result in additional and unexpected downtime for the equipment. The next step, preparation, is crucial for successful accomplishment of a service call, especially during field based repairs. The objective of this phase is to ensure that the correct maintenance resources will all be available during the service. Pathetic preparation makes the maintenance technician unable to rectify the defect. This leads to a failed service visit and a need for a follow-up visit, indicated as the return loop in the figure. Coming to the next step, gaining access to the equipment, maintenance service is carried out so that the maintenance technician moves to the equipment. In this phase, the technician needs to know where, when and how the equipment should be accessed. The fault diagnosis phase aims to accurately identify the problem and required corrective actions. It is an information intensive phase, where maintenance technicians traditionally rely on technical publications for information covering fault diagnosis procedures. The final steps are defect rectification, system testing and close up. These steps include adjusting, repairing or replacing equipment and ensuring that the repaired equipment is operating as it should. Eventually, the required documentation, e.g. service report and invoice, has to be generated [366].

Highlighting the benefits of condition based maintenance and its upbeat role in different stages of defect rectification, it is essential to underline that the goals and objectives of a condition based maintenance program should be fully developed and adopted by personnel who carry out the program and also upper management of the plant. Running a CBM program is not a justification for buying sophisticated, expensive equipment. Neither is the purpose of such program to keep a number of personnel busy with measuring and reviewing data from various machinery systems within the plant. The purpose of an effective CBM program is to minimize machinery failures, maintenance costs and lost production. It also improves production efficiency and product quality in the plant. This is realized by regular inspection and continuous monitoring of machinery condition, process efficiencies, and other parameters which define the operating condition of the plant. Using data acquired from critical equipment and machinery in a plant, incipient problems are identified and corrective actions are carried out to improve the reliability, availability and productivity of the plant. [442].

The identification of critical equipment and machinery is an important step towards implementing an effective CBM program. It is crucial to apply condition monitoring and nondestructive testing to these equipment and machinery first as they offer the best opportunity of justifying the often high levels of monetary investments needed. This approach can be used to make various CMTs and NDTs integral parts of an overall CBM conduct which allows management to determine the appropriate techniques to particular applications. This is seen extremely essential in establishing an effective CBM program. The advantage of this approach lies in the establishment of the credibility of condition monitoring and nondestructive testing in one area, which can then ease its introduction into others [491]. Having the critical facilities identified, the next step is to put appropriate CMTs/NDTs into action for diagnosis and condition assessment of these assets. This includes regular inspections and continuous monitoring which can identify areas of deficiency. Early identification of these areas provides an opportunity for targeted maintenance, which in turn can reduce the risk of unplanned downtime and increase the time available for production. Condition assessment is realized through utilizing various CMTs/NDTs and undertaking related machinery condition analyses and syntheses [367].

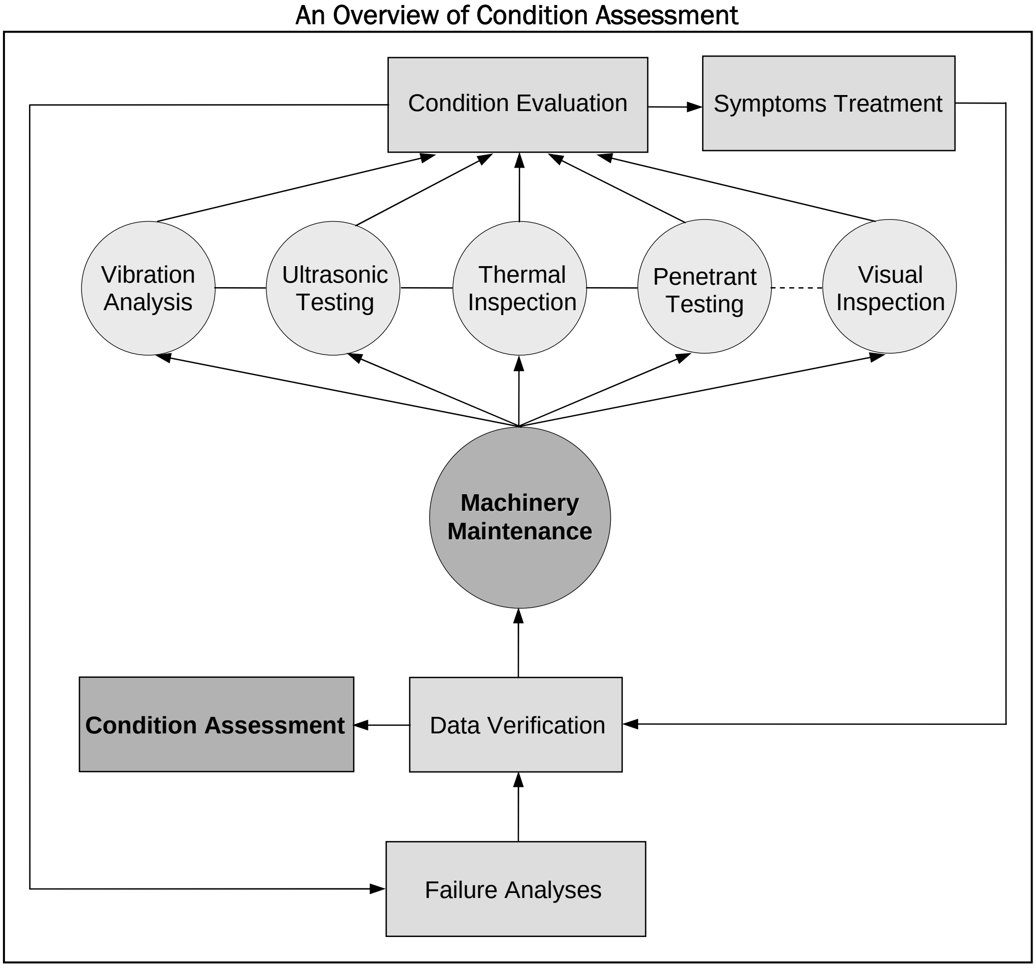


Figure 8 An overview of condition assessment procedure for machinery maintenance

4 The CBM Toolbox: A Systematics for CBM Management

The everyday increasing competition in industry and the compulsion of faster and higher return on investments for complex and expensive machinery, in addition to operational safety, health and environmental requirements, take for granted high availability of the production and processing machinery [38]. These targets are reached only if the machinery is kept in desirable operating condition by running an optimized condition based maintenance program. CBM, as a preventive and predictive action, strives to identify incipient faults before they become critical through structural condition assessment derived from condition monitoring techniques and nondestructive tests. An optimized CBM program requires early recognition of failures and accurate identification of the associated attributes in a feasible manner. The achievement of this proficiency in industry is still intricate and relatively expensive due to deficient information about the potential failures as well as inadequate knowledge or improper application of different CMTs and NDTs.

In view of that, a new toolbox has been developed to facilitate efficient planning and sustain effective implementation and management of CBM programs in production and processing industries. The CBM toolbox consists of three major tools and embraces a utilization procedure. The first tool is a series of statistical failure analyses which uses the failure history data available in a plant's information system to generate valuable information in tabulated and graphical postures. The second tool is a repository filled with expert knowledge about different CMTs and NDTs formatted in a way that in addition to the concept of each technique, its applicability, detectability, and its pros and cons are expressed. The third tool is an object based problem and cause analysis whose outcome is tabulated problem-cause relationships associated with particular machinery objects. Every now and then, these tools are standalone employed in different industries for a variety of purposes. But yet, they have not been employed all together as a package to optimize planning and managing CBM activities and ease the tasks of maintenance personnel.

4.1 Overture of the Toolbox

The CBM toolbox has been pioneered as an innovative systematics which is partially driven by expert knowledge. It is considered to be 'innovative' since it is new and creative in the way it is designed and configured. 'New' in the sense that the CBM toolbox is replacing or supplementing some methodologies that may already exist but in an effectively modified and combined structure which constitutes for a revived, different and improved format. 'Creative' in the sense that it is resourceful and is able to generate essential information, knowledge and intelligence. Moreover, its arrangement denotes use of thoughts and imagination in selecting the tools and designing the approach to systematically facilitate managers and planners as well as maintenance and operation personnel with planning, controlling and undertaking the activities related to condition based maintenance.

As mentioned above, the CBM toolbox is consisted of three major tools or segments. The first tool is a series statistical failure analyses (SFA) which uses failure history data available in information system of a plant to generate valuable information in tabulated and graphical postures. The SFA has been developed as formulated Excel files. The second tool is a knowledgebase filled with expert knowledge about different condition monitoring techniques and nondestructive tests used in the framework of condition based maintenance. This knowledgebase has been developed as searchable Word files; though, in the future it is possible and indeed it is more useful to convert it into software. The knowledgebase designates the applicability, detectability, advantages and disadvantages of different CMTs and NDTs in addition to other extensive information.

The CBM toolbox also contains a small financial analysis tool and an inclusive selection matrix which help identifying the most appropriate condition monitoring technique or nondestructive test to be exploited in a particular case (i.e. for a specific machinery of certain material and particular failure mode in an explicit business environment). These have been designed as smart Excel files with integrated formulae. And eventually, the third tool is object based problem and cause analysis (OBPCA) whose outcome is tabulated problem and cause correlations associated with particular machinery objects. The OBPCA has been developed as modifiable Excel files. This can be particularly useful to establish optimal problem and cause lists in a plant's information system. Figure 9, in the next page, provides an overview of the CBM toolbox.

The CBM Toolbox Overview

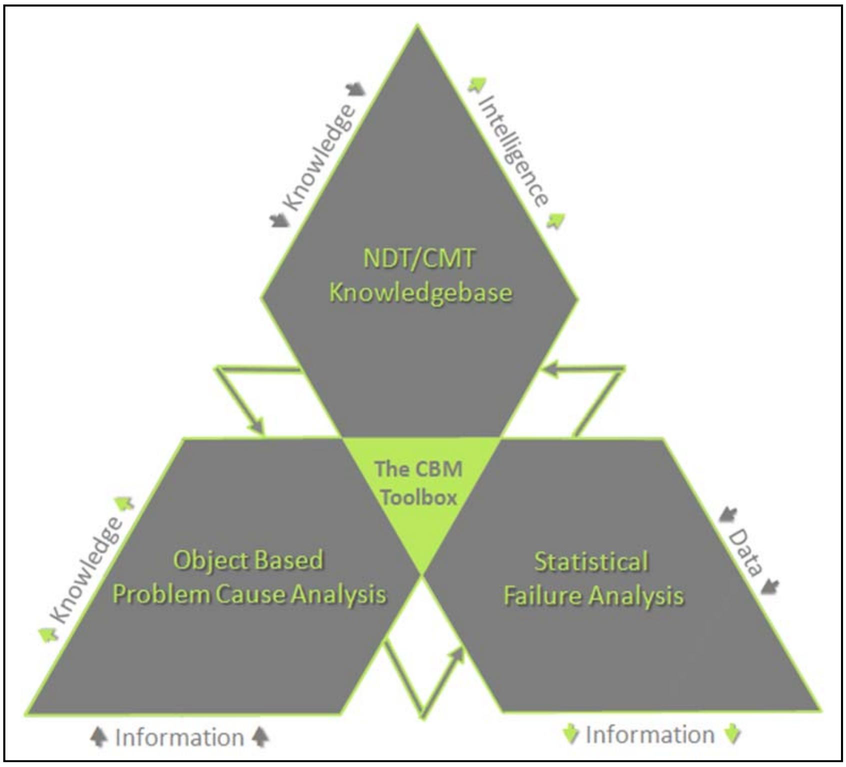


Figure 9 An overview of the structure and the information flows of the CBM toolbox

4.2 Structure of the Toolbox

In the CBM toolbox, the first tool is a series of statistical failure analyses uses failure history data available in information system of a plant to generate valuable information in tabulated and graphical postures. This segment is consisted of 7 different fragments as different analyses incorporating machinery failure data. They can be listed as: time based failure analysis (TBFA), station based failure analysis (SBFA), object based failure analysis (OBFA), problem based failure analysis (PBFA), cause based failure analysis (CBFA), statistical problem cause analysis (SPCA), and time based maintenance analysis (TBMA). This tool facilitates the maintenance personnel with the ability to identify the most critical facilities, stations, machinery objects, problems and their causes plus their suitability to be maintained by planned maintenance or monitored by various CMTs and NDTs.

The second tool, the CMT/NDT knowledgebase, contains 14 major condition monitoring techniques and nondestructive tests used for the purpose of condition based maintenance and employed in different production and processing industries that themselves may be consisted of a variety of methods. On the whole, the knowledgebase includes expert knowledge about more than 45 different methods and techniques which has been structured and categorized in a way to make it as useful as possible, and thus, turn it to intelligence. These major NDTs and CMTs include: acoustic emission testing (AT), electrical inspection (EI), electromagnetic testing (ET), laser inspection (LI), leak testing (LT), magnetic particle testing (MT), penetrant testing (PT), radiographic testing (RT), stress wave analysis (SA), thermal inspection or thermography (TI), tribological testing (TT), vibration analysis (VA), visual/optical inspection (VI), and ultrasonic testing (UT).

In addition, a compact financial analysis tool and a CMT/NDT selection matrix are developed and supplemented. Due to considerable initial investments and particular training and skill required, cost of running a nondestructive test or condition monitoring technique is substantial; hence, there must be huge recompense to be gained in minimizing the amount of corrective or planned maintenance that is used to be performed and maximizing the CBM-related activities. Besides, this must be balanced against the risks of machinery failure and the consequences of failure which are potentially very undesirable. For this reason, a tool, as a formulated Excel sheet, has been developed to analyze each test from financial perspective. The compact financial tool calculates (1) cost effectiveness, (2) return on investment, and (3) payback period for each CMT/NDT.

The CMT/NDT selection matrix is another tool designed to standardize and ease the decision making process in selecting the most appropriate CMT/NDT for a particular case in a plant. This tool, which has been developed as smart Excel sheet, evaluates the overall effect of different criteria that are central to decide on the most suitable test or technique to be used to prevent a certain type of problem. These criteria, which are clearly defined, include: usability, feasibility, efficacy, compatibility, and safety. The selection matrix incorporates a special weighting and ranking system based on which a final factor called "UFECS" is calculated. Among all available alternatives, the test with the largest UFECS factor will be the most appropriate one to be used for a specific case in a particular company.

The third tool, OBPCA, provides tabulated problem and cause correlations associated with particular objects. This involves identifying all possible problems, choosing the most common problems, determining the probable causes of these problems, and eventually correlating the problems and cause of these in a specific format which is compact and easily understandable. It is notable that a specific problem associated with a particular machinery object may have not only one probable cause but a wide variety of causes. This tool helps having higher quality and more reliable data entering the plant's information system. As a result, the information which is provided by statistical failure analysis will definitely have higher quality and reliability as well. The decisions which are taken based on such information are more consistent and trustworthy. Consequently, the CMT/NDT knowledgebase can be more effectively used to identify the most appropriate alternative solutions. The tools of the CBM toolbox are extensively described in the coming chapters.

The CBM Toolbox in Details

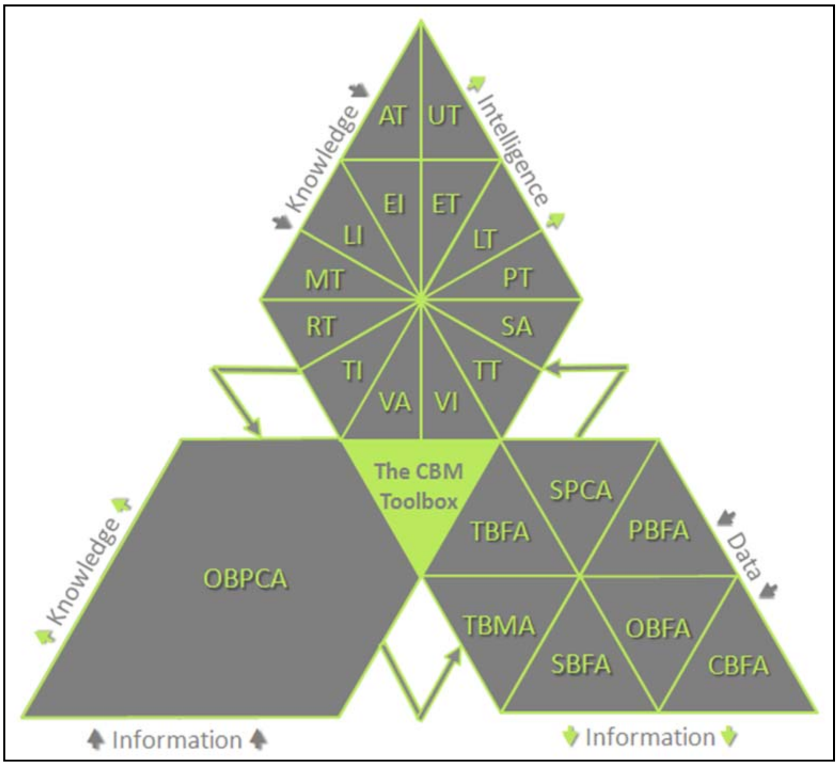


Figure 10 Detailed structure and the information flows of the CBM toolbox

4.3 Information Flows of the Tools

In the CBM toolbox, some of the intermediate information provided by each tool or segment is used to improve or conclude the other ones in a progressive manner. To illustrate, one can consider the followings: The tabulated lists generated through OBPCA can be used to improve the quality of problem and cause data in the information system which is used by the statistical failure analysis, and thus, improve of which provides more reliable analysis results. Over time, some extra information about new problems or discovered causes entered in the information system (by plant technicians) and the expert knowledge attained through the continuously updated CMT/NDT knowledgebase can be used to further develop the OBPCA lists. The high quality information obtained from the improved SFA in joint with the knowledge will result in effectively-run condition based maintenance program.

Indeed, there are two different information flows related to the CBM toolbox. There is an external information flow, via which particular data, information and knowledge come to the mentioned segments of the toolbox and the generated information, knowledge and intelligence go out. There exists also an internal information flow, through which the generated outcomes of each segment is either directly used by another one or indirectly affect the quality and accuracy of the outcomes being generated by other tools. It is essential to underline that the term information is conventionally used to refer to all modes of descriptions or representations from raw signals to knowledge and understanding. It is important to recognize that information can be sorted out into different classes based on their level of intelligence content which makes different value in decision making processes.

Various levels of information can be sorted in a hierarchical fashion, which at different stages of the hierarchy supports decisions at various operational levels. Noise, which is placed at the bottom of the information hierarchy, mainly consists of any unwanted data and no useful information is expected out of it. Data are symbols that represent information for processing purposes, based on implicit or explicit interpretation rules [219], [665]. Information is data with formal and explicit semantics. Information can be communicated between two or more partners [219]. Semantics is a key aspect of information because the partners need to have a unique and unambiguous understanding of every piece of information. Knowledge extends beyond the notion of information by including relationships between pieces of information [665]. In an engineering context, knowledge includes taxonomies, rules, and constraints and is also considered as value-added information for decision making. Intelligence, also referred to as wisdom, is the development of grasp of the overall situation with the ability to predict and project in the given domain [2], [43], [219].

The Information and Functional Hierarchies

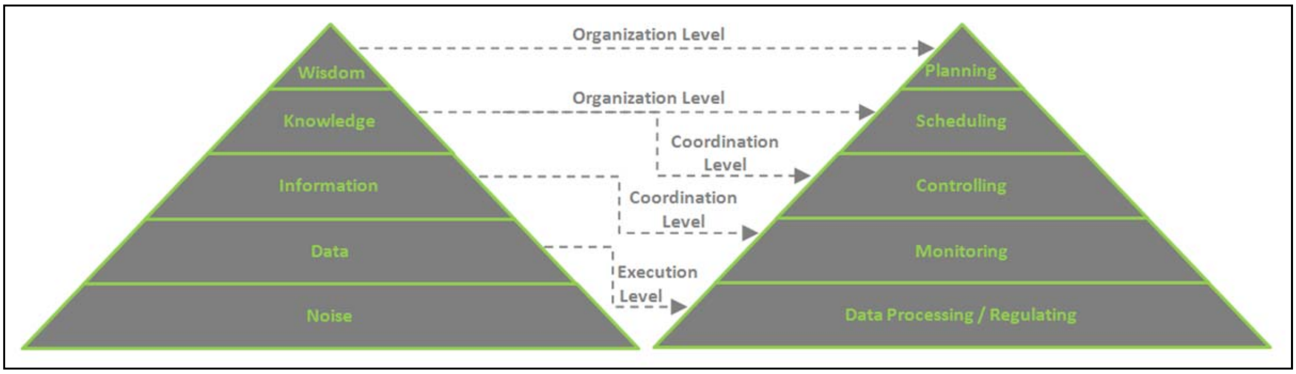


Figure 11 Information and functional hierarchies with designated usefulness in operational levels [219], [511]

To be more precise, in the first segment of the toolbox failure and maintenance related data available in the information system is taken out and effectively analyzed to craft comprehensible information, interpretation of which is not only used to rise and solve maintenance related issues but also it is utilized to assist the management with enlightening various managerial concerns (e.g. from spare part and inventory management to performance evaluation of undertaken activities). In the second segment, large amount of expert knowledge from a wide range of sources are gathered and formatted in a way to create higher quality knowledge which is easier to be used and understood, or in other words, intelligence. In the third segment, the information associated with potential failure modes of different machinery objects and their probable causes is collected from diverse sources and tabulated in a handy way to produce intensive knowledge about object based failure modes and causes.

Coming to the internal information flow of the toolbox, the knowledge generated by the OBPCA helps enhancing the quality, accuracy and reliability of the data generated in the information system which is used by the SFA. Higher the quality and reliability of the data coming to the SFA results in higher quality and reliability of the information it generates. With reliable information in hand from SFA (e.g. the information about the most critical machinery part and its most frequent problem), one finds the most appropriate solution to predict and prevent a particular problem in the CMT/NDT knowledgebase. The knowledge generated by or gathered in the first and second segments which are continuously being updated by professionals, is also used to revise and renew the information in the third segment (e.g. information about the recently discovered failure modes and causes). Hence, in this way the internal information flow of the CBM toolbox is closed as an inner loop.

4.4 Utilization Procedure of the Toolbox

The utilization procedure of the CBM toolbox, as shown in figure 12, is straight forward and can be accomplished in four phases. In the first phase, it begins with undertaking a statistical failure analysis of a facility, identifying its critical stations, machinery objects, occurred problems and causes according to their frequency, determining their attributes and criticality degree, and checking their suitability to be monitored, predicted and prevented by planned or condition based maintenance. After identifying the most critical machinery object and their associated problems, e.g. valves and leakage, the responsible analyst moves to the second phase. In this phase, by doing a search in the CMT/NDT knowledgebase, all the alternative condition monitoring techniques and nondestructive tests which can be used to monitor, predict and prevent leakages from valves are figured out.

In the third phase, using the financial analysis and selection matrix tools, the most appropriate technique among all alternatives for discovering potential leakages from valves in the plant (i.e. taking into account the company's conditions, preferences and requirements) is selected and initiated. In the last phase, according to the information derived from the undertaken statistical failure analysis or attained through this procedure, the OBPCA tables and related catalogs for valves are updated and any modification of problem and cause lists in the information system is taken place. If there was not a previously undertaken OBPCA for valves, it is performed and achieved in the fourth phase. In fact, this phase has a more complementary function to refine the quality of the information which will enter the plant's information in the future. Or in other words, it helps continuous refining of the quality of information passes through former phases, and thus, achieving more reliable results.

Utilization Procedure of the CBM Toolbox

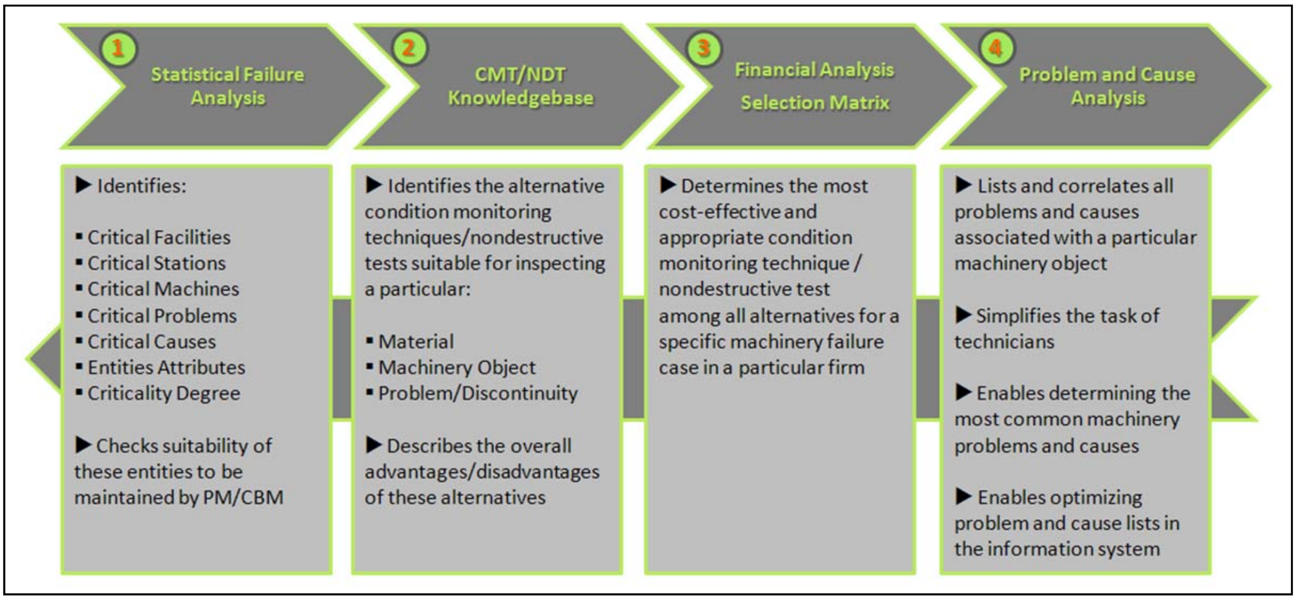


Figure 12 Different phases of utilizing procedure of the CBM toolbox in practice [324]

5 Statistical Failure Analysis for the CBM Toolbox

Statistics is decision making which is based on groups of numbers. Statistical analysis tries to answer what the numbers say, what the trends are, and what conclusions can be drawn. Statistical failure analysis is a priceless tool which can be employed not only by maintenance department of a manufacturing or processing plant but also by other departments which deal with production, and spare part and inventory management. The resultant information out of such analysis provides an overview of the condition of different facilities in a plant; plus, such information can be used to measure how effective employees of a plant work, if they need any further training or if the management itself has to define its operational policies and tactics in different ways.

Within the framework of this research, an uncomplicated statistical failure analysis (SFA) is fruitfully used for maintenance related issues. As it is shown throughout this chapter, such a SFA itself contains different analyses or tools, each of which provides broad range of information in graphical or tabulated manner that can be used for a variety of purposes. In fact, the visual presentation of data is extremely important in statistics as it enables the stakeholders to discern trends, significances and trends they might not see by just looking at the numbers. Besides, visual presentation helps the people with different technical backgrounds easily understands the ideas and the important issues.

These analyses reveal some indispensable information which is sealed in thousands lines of data in an information system as notices, orders, feedbacks, events, failure histories and etc. It is basically learning from past, to be fully equipped for future challenges and to be able to deal with potential down-beating events such as major failures. It is extremely crucial to underline that here the endeavor is to show some basic but very useful statistical tools and their usage, and the different types of essential information they can provide. The designed SFA tool is a system which requires some inputs and provides some outputs. The aim of this work was to structure such a SFA system but not to improve the quality of input data at this stage. There is no doubt that for any statistical system the reliability and usefulness of the output information highly depend on the quality and length of the input data; however, the structure of the system itself is independent of any input.

Taking into account what has been mentioned, a few issues have to be explained before addressing different analyses which have been integrated in the SFA tool. First is that the maintenance related data in the used information system which has been available since first of July 2005, although not perfectly structured, but is precious input for any statistical analysis. The results of the undertaken analyses which are provided in the coming pages divulge the importance of such a system and the significance of its contribution in creating effective strategies and making right decisions in maintenance and production. Vividly, as said before, higher the quality of data fed into the information system, higher the quality of the information that can be retrieved; nevertheless, having a systematic SFA tool is equally important as the quality of input data can be gradually improved in time.

The second issue is the time based length of data in an information system. As the considered system was practically brought into the service in July 2005, the length of data in time is not so long. If a year is taken into account as a cycle, there would be only four cycles of time within the studied period, i.e. from 01.07.2005 to 30.06.2009 at the time the statistical failure analyses were undertaken. However, it is possible to shorten the length of a defined cycle and attain more cycles per a period of time. Hence, there can be 16 cycles of quarter annum or 48 monthly cycles out of the mentioned period. Analyses of cycles usually expose interesting information about time attribute of a phenomenon if there exists any, in this case machinery failures.

Besides, within the information system of TRW-Schalke, it is possible to distinguish between two failure types which are denoted with the terms major and minor failures by the author. Major failures are defined as the failures that stop equipment or machinery from working. Minor failures are those which do not stop any equipment or machinery from working but disturb their functionalities, working quality, speed or precision. Note that here the quality, effect or severity of a failure is considered to categorize it as either a major or minor failure. From the author's perspective, and as used throughout this chapter, the frequency of occurrence is related to how critical a failure is; and it does not signifies a failures qualitative effects on the production process. In coming pages, it is explained how to identify the two different types of failures and what can be interpreted from their related data.

The pilot facility, for which the maintenance related data has been retrieved from the information system of TRW-Schalke and thoroughly analyzed, is the P1 facility. The facility was set up in the year 1992, and since then, it has been continuously in service. It is consisted of 28 stations, through which some parts of a steering system are assembled. Figure 13 presents the layout of this facility. Seven different statistical analyses have been undertaken to diagnose the facility. These analyses are explained in the coming subsections.

Layout of the P1 Facility

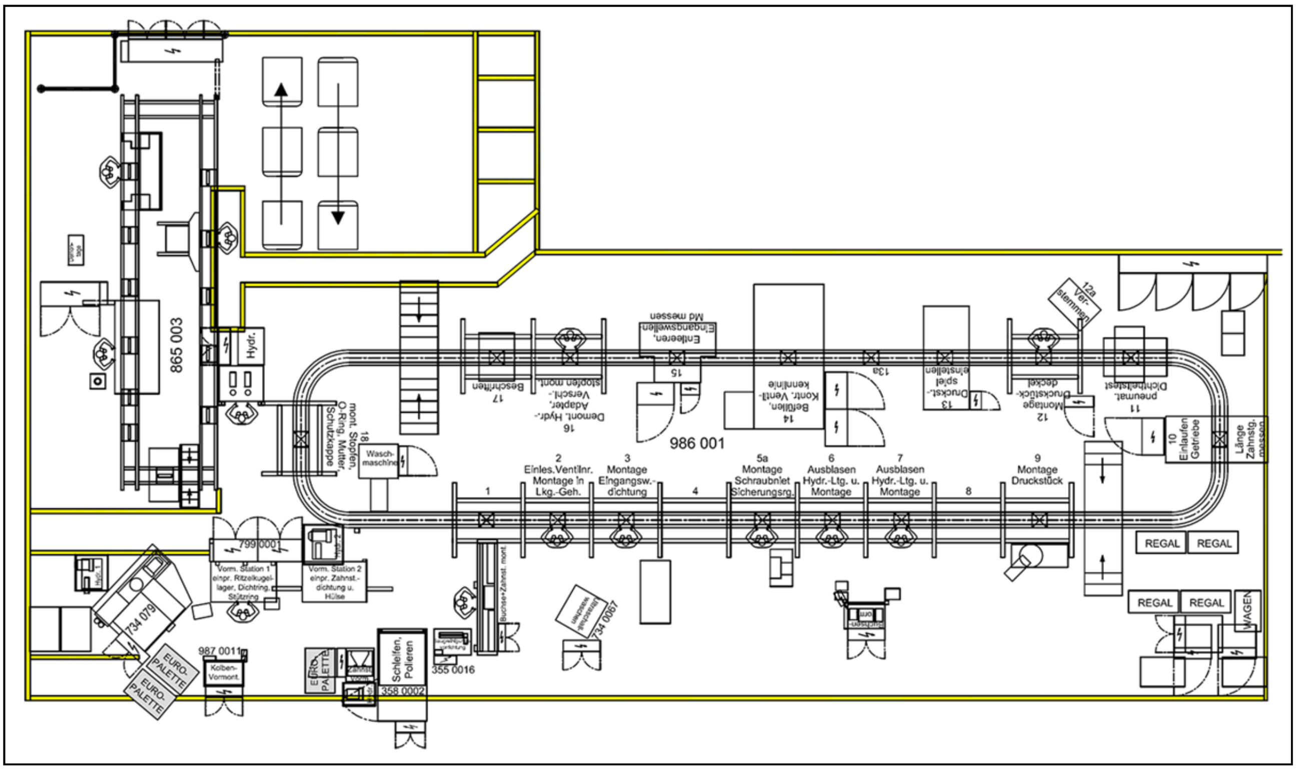


Figure 13 A recent layout of the P1 facility, revised in April 2009.

Before going through the analyses in details, it has to be highlighted that the statistics used here is in form of descriptive statistics which is used to describe and summarize the main features of a collection of sample data numerically and graphically. Numerical descriptors include mean and standard deviation for continuous data, while frequency and percentage are more useful in terms of describing categorical data. Note that descriptive statistics is distinguished from inferential or inductive statistics, which is used to support inferential statements about the population that the data is thought to represent.

5.1 Time Based Failure Analysis

The first step towards undertaking a comprehensive statistical failure analysis is to graphically project the number of all H1 transactions which have been made in the plant's SAP system. There are three types of transactions: notifications, orders, and confirmations. H1 transactions are linked to the major failures in the plant; when a major failure occurs, an H1 notification is sent in the SAP system, the notification is then assessed by maintenance department and if approved, an order is placed for which one or more repair completion confirmations are provided by technicians later on. Each of these transactions incorporates some important information which can be used for different purposes and by different departments in a plant.

For H1 transactions, number of orders is a direct indication of number of major failures; number of notifications is a measure of worker's verdicts if a problem was a major failure or not; and, number of confirmations is basically number of feedbacks provided by a technician on major failures. The most favorable situation is not only when number of H1 notifications and orders is decreasingly low but also when number of sent notifications and placed orders are equal. The first indicates a small number of major failures and also an improving situation, while the second shows how well trained are the machinery operators as their judgment matches the sentence of experienced maintenance staff.

From 01.07.2005 to 30.06.2009, taking into account the number of H1 transactions for the P1 facility, there were totally 518 notifications, 498 orders, and 910 confirmations. Making an average over four years, one can easily see that there were 11 notifications, 10 orders and 19 confirmations per month. Basically, when the number of sent notifications is higher than the number of placed orders, this is interpreted as workers' mistake in notifying the major failures; in other words, there were notifications reviewed by maintenance department and considered not to be at H1 level or a major failure. Such a difference between numbers of notifications and orders in a definite time period (e.g. a month) may be resulted from delayed placement of orders in the system as well. However, such delayed placements should not be consented particularly in the important case of H1 notifications. On the other hand, when number of placed orders is more than number of sent notifications, it means that there were notifications of minor failures at H2 level which indeed had to be sent as major failures at H1 level. For the P1 facility the first argument holds true: during the studied period and on average, there had been one extra H1 notification per month which was mistakenly sent. This number counts for almost 10% of sent H1 notifications per month. Figures 14 and 15 show the monthly inquiry and the trend of H1 transactions for the P1 facility over successive four years.

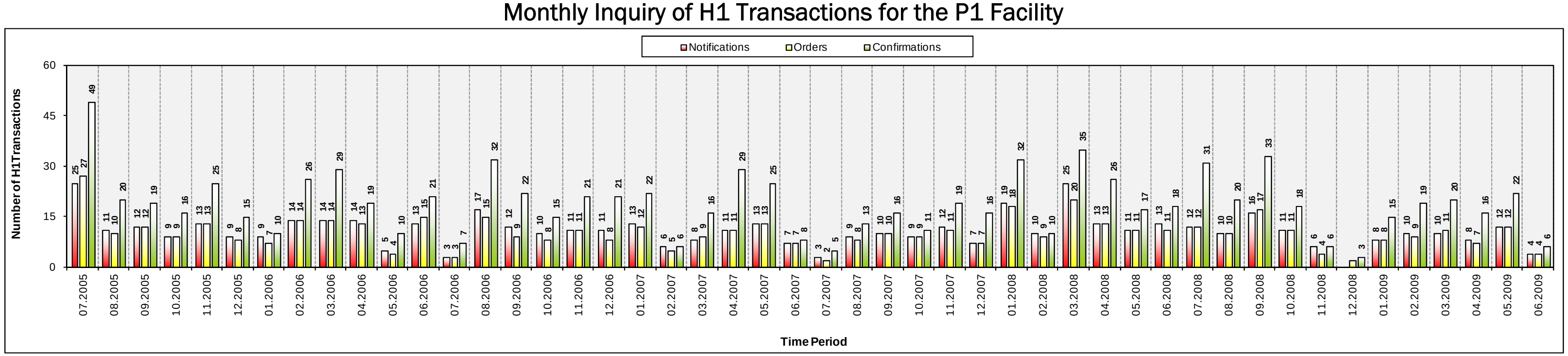


Figure 14 Number of different H1 transactions (i.e. notifications, orders and confirmations) per month for the P1 facility from 01.07.05 to 30.06.09

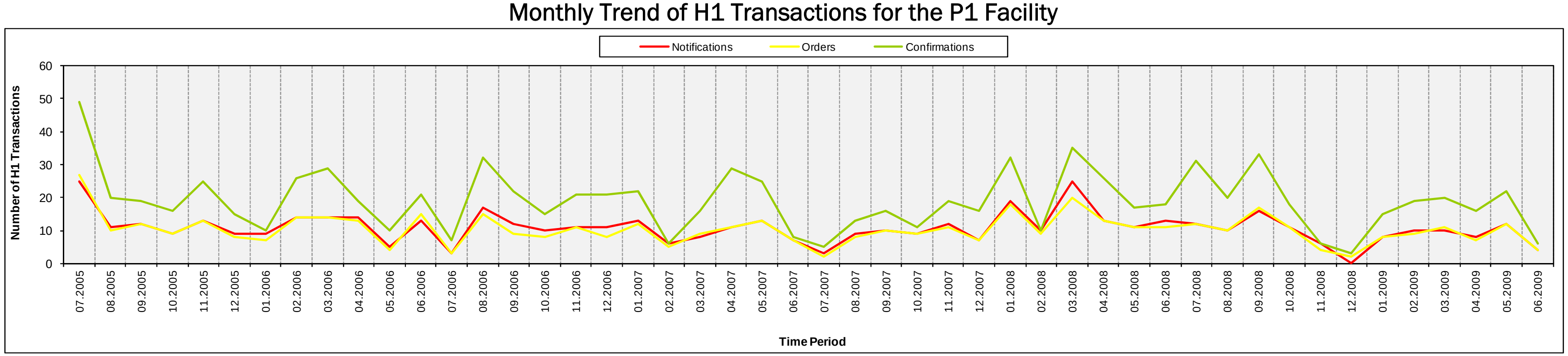


Figure 15 Tend of different H1 transactions (i.e. notifications, orders and confirmations) on a monthly basis for the P1 facility from 01.07.05 to 30.06.09

Within the same period of time and for the same facility, the number of H1 transactions on a quarter-annum and a semi-annum basis has been shown in figures 16 and 17. This can provide a clearer image of the overall situation; for example, there can be some notifications sent to the system on the last day of a month and their order were placed on the first day of the other month for which inherent corrections are made in these graphs. Making an average over four years, there were 32 notifications, 31 orders and 57 confirmations per quarter-annum and 65, 62 and 114 respective transactions per semi-annum. From figures 16 and 17, it can also be concluded that the situation is not very far from the most favorable one regarding the numbers of notifications and orders (i.e. to have equal number of notifications and orders), but there is still place for improvements. The below figures show that from the 3rd quarter or 2nd half of the year 2008 equality of the number of sent H1 notifications and placed orders has been almost grasped. However, the number of completion confirmations has been always considerably more than the one of orders due to receiving separate confirmation from every single technician who was involved in repairing a damaged machinery or equipment. If all completion confirmations of an order are gathered and merged as a single one, accessing and extracting all the essential information will be considerably alleviated. The information thawed in every confirmation transaction is of great importance to have effective failure analysis and thus consistent results.

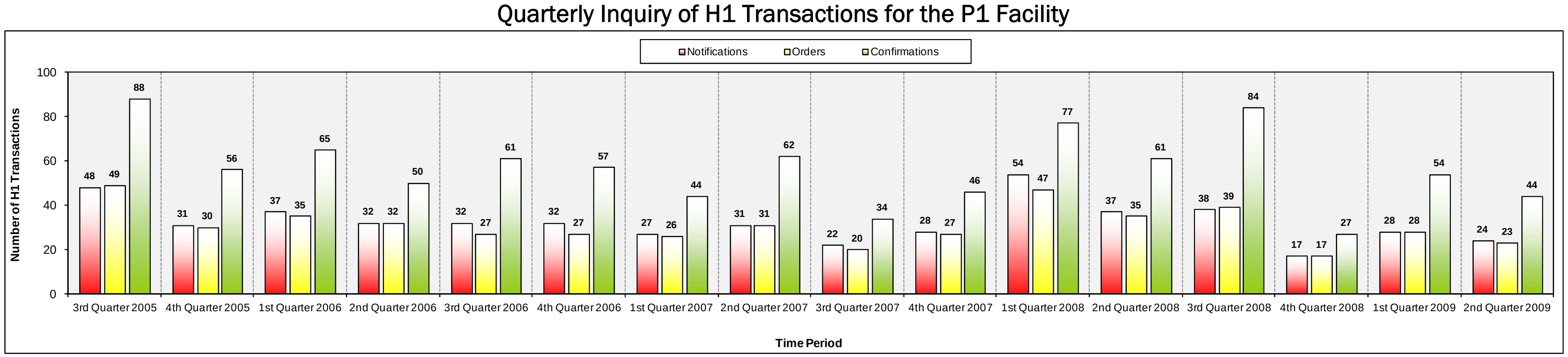


Figure 16 Number of different H1 transactions (i.e. notifications, orders and confirmations) per quarter-annum for the P1 facility from 01.07.05 to 30.06.09

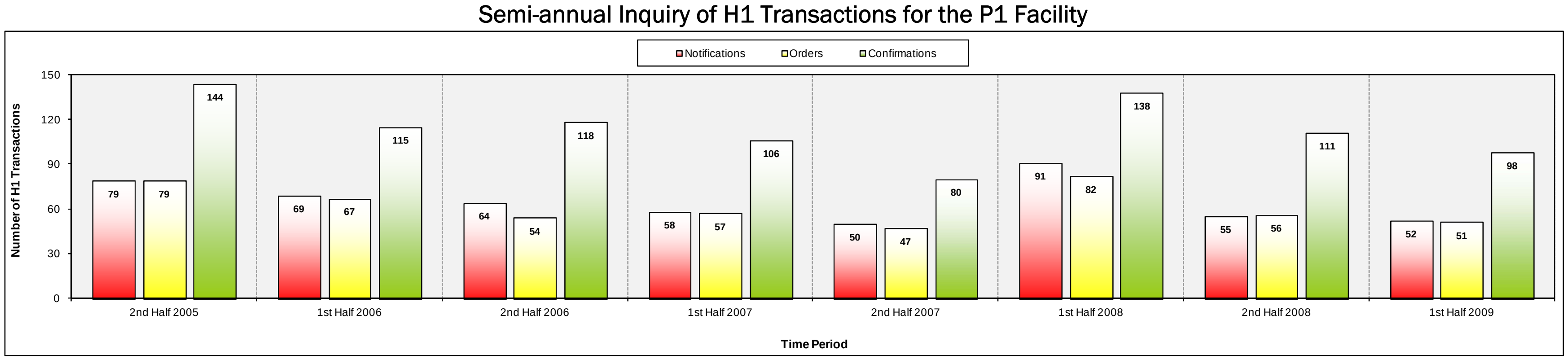


Figure 17 Number of different H1 transactions (i.e. notifications, orders and confirmations) per semi-annum for the P1 facility from 01.07.05 to 30.06.09

Essentially, number of major failures occurred in a facility can be traced by number of H1 orders in the SAP system. It has to be highlighted that an H1 notification is not necessarily an indication of a major failure since a wrong notification can be always sent to the system by workers. However, an H1 order is always a good indicator as it is placed in the SAP system by an expert employee in maintenance department after proficient assessment. Figure 18 shows the number of major failures that has been occurred in the P1 facility per month between 1st of July 2005 and 30th of June 2009. The total number of major failures within this period is 493 which reckons for 12 per month on average. The largest number of major failures occurred in July 2005 as 27 and the smallest in both July 2007 and December 2008 as only 2. Within the studied period, the most critical month has been March and the least critical month has been December with respective 14 and 6 major failures occurrence on average. Figure 19 represents the same numbers on a quarter-annum basis. It also shows that since the 1st quarter of 2006 there had been almost a steady decrease in number of major failures in the P1 facility till the drastic increase in the 1st quarter of 2008, after which this number stayed relatively high for the next two quarters. Indeed, reasons behind such an abnormality can be investigated by maintenance department in order to prevent similar causes in the future. Between 01.07.2007 and 30.06.2009, the most critical quarter has been the 1st and the least critical quarter has been the 4th with according 34 and 25 major failures occurrence on average.

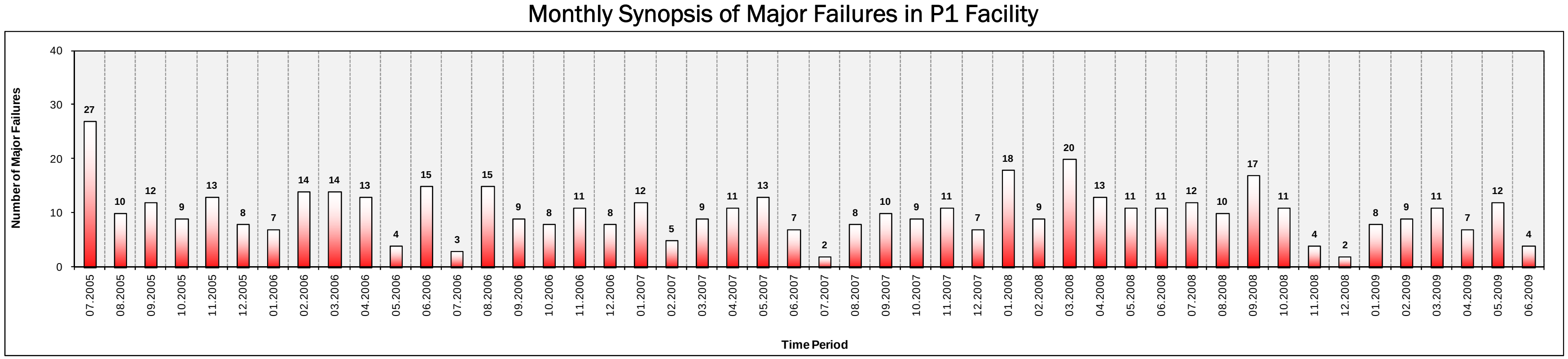


Figure 18 Number of major failures per month for the P1 facility from 01.07.05 to 30.06.09

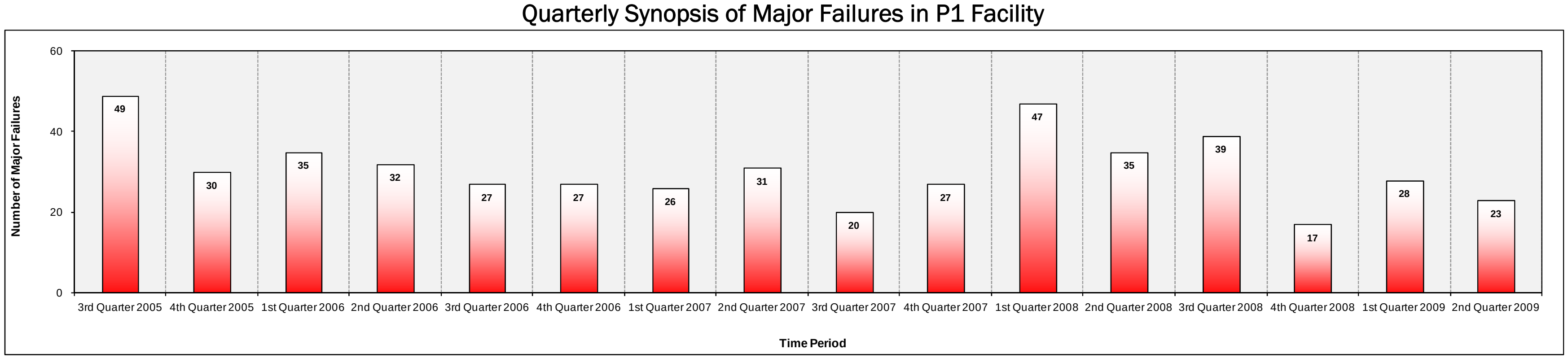


Figure 19 Number of major failures per quarter-annum for the P1 facility from 01.07.05 to 30.06.09

The next step is to analyze the H2 transactions which are indeed related to minor failures or disturbances in a facility. From 01.07.2005 to 30.06.2008, there were totally 1559 notifications, 1543 orders, and 2026 confirmations for the P1 facility. Making an average over four years, the mentioned numbers reckons for both 32 notifications and orders, and 42 confirmations per month. By a simple comparison, it can be seen that within the same period of time there have been almost three times more disturbances or minor failures than major failures. When the number of H2 notifications in a month is higher than number of H2 orders, it can be due to neglecting of some of less important notifications by maintenance department. Moreover, sometimes when a minor failure occurs and a technician is nearby, he fixes the problem without an order being placed in the system by maintenance crew. In the same scenario, it can happen that a technician fixes a minor problem and then informs the maintenance department so an order is placed in the system and a confirmation is sent without having a notification. This is how number of orders can be more than number of notifications. Again, number of completion confirmations is usually greater than number of orders since for a particular problem there can be more than one technician involved in repair. Vividly, in the most optimal case the number of H2 notifications and orders has to overlap. Figures 20 and 21 show the monthly inquiry and the trend of H2 transactions for the P1 facility over four successive years. From September 2005 onwards, number of H2 transactions shows a gradual decrease although it is not very unremitting.

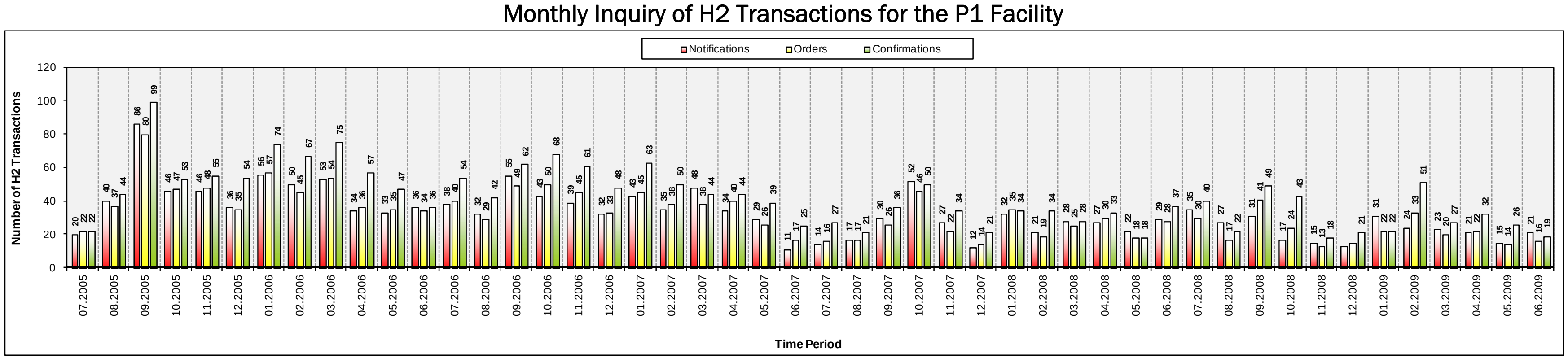


Figure 20 Number of different H2 transactions (i.e. notifications, orders and confirmations) per month for the P1 facility from 01.07.05 to 30.06.09

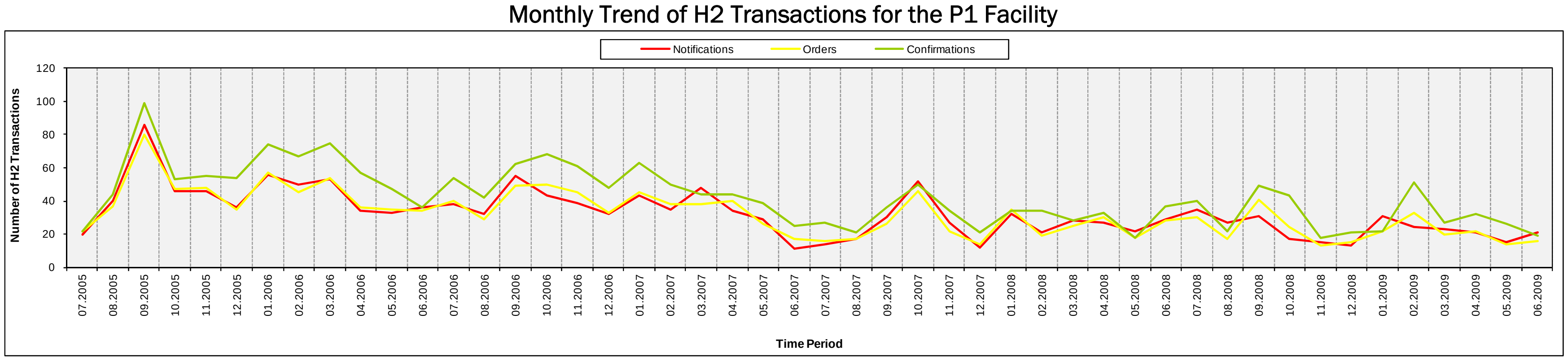


Figure 21 Trend of different H2 transactions (i.e. notifications, orders and confirmations) on a monthly basis for the P1 facility from 01.07.05 to 30.06.09

Within the studied period and for the P1 facility, the number of H2 transactions on quarter-annum and semi-annum basis has been indicated in figures 22 and 23. Making an average over four years, there were 97 notifications, 96 orders and 127 confirmations per quarter-annum and 195, 193 and 253 respective transactions per semi-annum. The figures below show that there has been usually a considerable difference between the number H2 notifications and orders in comparison with the case of H1 transactions. This is relatively far from the most favorable situation regarding numbers of notifications and orders which is to have equal number of both transactions; therefore, definite improvements are required. The number of completion confirmations has been always more than the one of orders, however, with smaller differences comparing to the number of H1 transactions. As before, the reason behind having a larger number of H2 confirmations than orders is receiving separate confirmation from every single technician who was involved in fixing a minor failure. Nevertheless, as there is usually less number of technicians needed to fix a minor failure than a major one, the overall number of H2 completion confirmations is less than that of H1s. Again, gathering all the completion confirmations of an order and merge them as a single confirmation can be essential as it will ease accessing and extracting all incorporated information in various completion confirmations of a particular order.

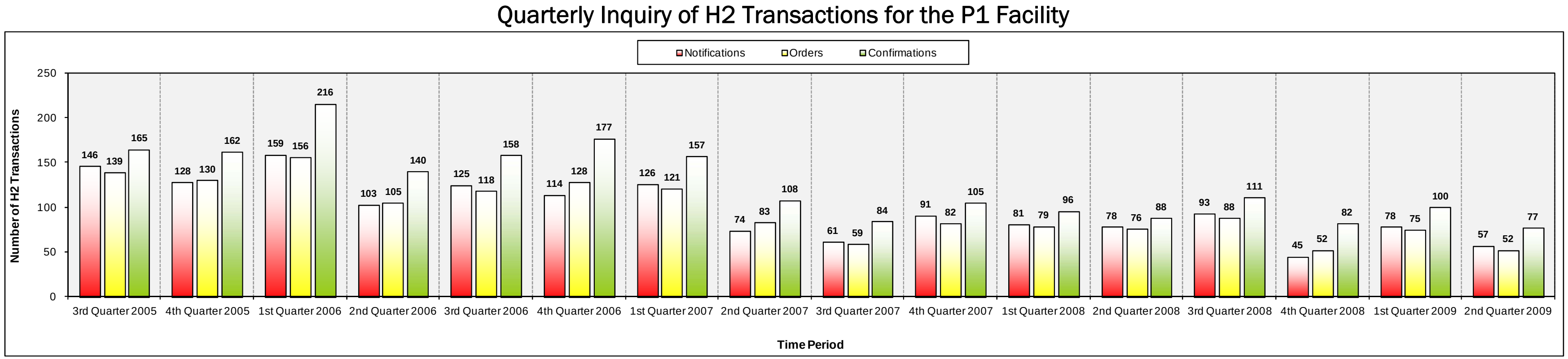


Figure 22 Number of different H2 transactions (i.e. notifications, orders and confirmations) per quarter-annum for the P1 facility from 01.07.05 to 30.06.09

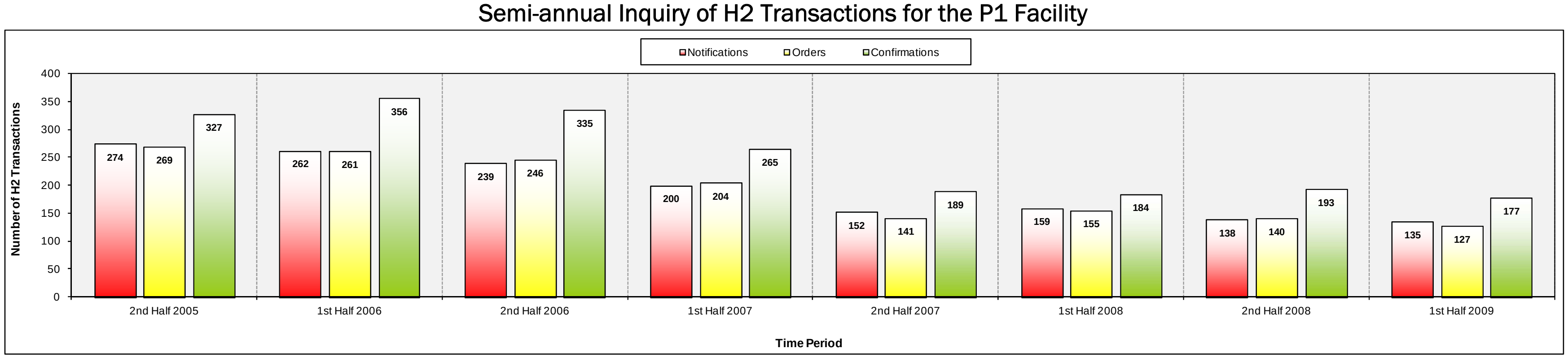


Figure 23 Number of different H2 transactions (i.e. notifications, orders and confirmations) per semi-annum for the P1 facility from 01.07.05 to 30.06.09

Number of minor failures occurred in a facility can be traced by number of H2 notifications in the SAP system. In contrast to the case of H1 notifications and major failures, an H2 notification is a direct indication of a minor failure as making a mistake notifying a minor failure is not probable. However, sometimes due to the lack of importance or pace of repair, an H2 order is not placed in the SAP system although a disturbance has been notified. Hence, number of H2 notifications is the best indication of number of minor failures in a facility. Figure 24 shows the number of major failures that has been occurred in the P1 facility per month between 01.07.2007 and 30.06.2009. The total number of minor failures within this period is 1559 which reckons for 32 per month on average. The largest number of minor failures occurred in September 2005 as 86 and the smallest in June 2007 as 11. Within the studied period, the most critical month has been September and the least critical month has been December with according 51 and 23 minor failures occurrence on average. Figure 25 indicates the same numbers on a quarter-annum basis. It also shows that since the 1st quarter of 2007, there had been an unsteady decrease in number of minor failures in the P1 facility. The most critical quarter has been the 1st and the least critical quarter has been the 2nd with respective 111 and 78 minor failures occurrence on average. It must be clear that the time-length of the available data is not enough to reprove the mentioned critical months and quarters as concrete facts. Longer the length of the data more reliable statistical information can be retrieved from that data.

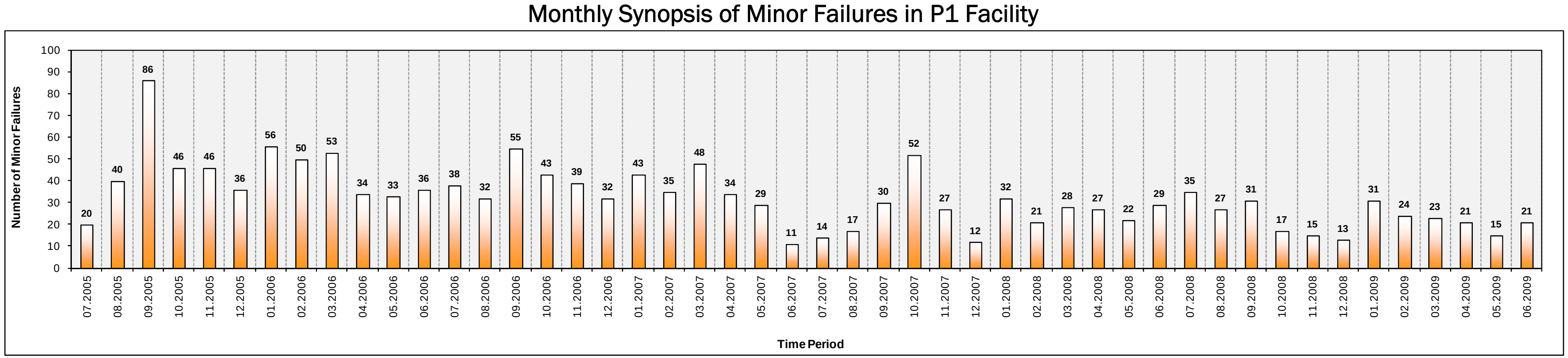


Figure 24 Number of minor failures per month for the P1 facility from 01.07.05 to 30.06.09

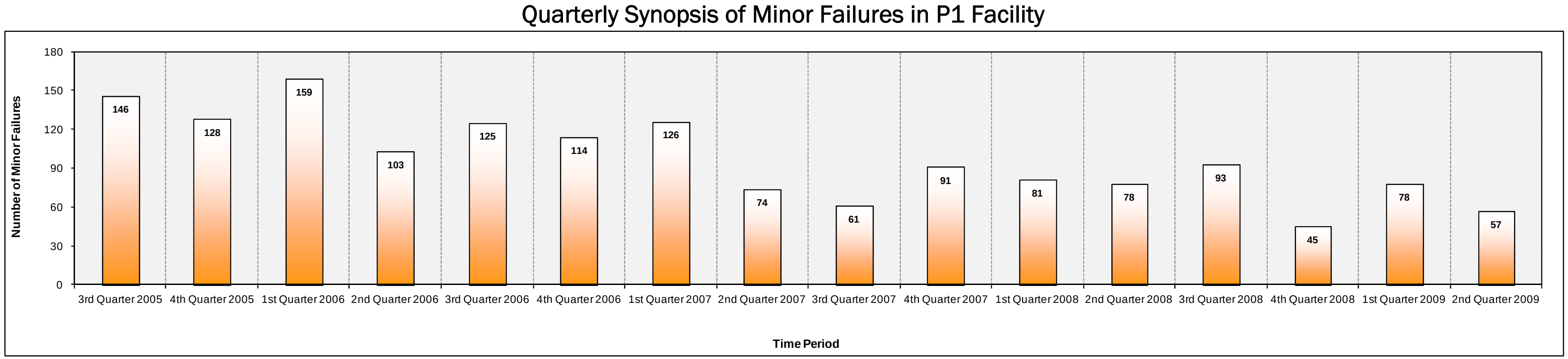


Figure 25 Number of minor failures per quarter-annum for the P1 facility from 01.07.05 to 30.06.09

In the SAP system, a planned maintenance (PM) activity is placed via an H3 order. After a particular planned maintenance activity is undertaken one or more completion confirmation is sent to the system by technicians who are responsible for the scheduled maintenance event. All the H3 transactions created in a definite period of time can be shown on a graph to provide an overview of the PM activities. This has been done on a monthly and quarterly basis as shown in the figures 26 and 27 correspondingly. It is always expected to have more confirmations than orders since there are usually more than one technician and more than one problem to solve during a single PM event. The figures below interestingly show that before August 2006 there has not been even a single PM activity undertaken in the P1 facility or if there was, it had not been placed in the information system. Considering PM activities from 08.2006 to 06.2009, there were totally 64 orders and 176 confirmations for the P1 facility. Making an average over 35 months, the mentioned numbers reckons for 2 orders and 5 confirmations per month. The average number of H3 transactions on a quarter-annum basis can be calculated as 5 orders and 15 confirmations. Here the issue is if the PM activities had been optimally scheduled or not. Evidently, planning and undertaking a PM activity is always matter of available resources; nevertheless, priority should be given to the most critical stations keeping an acceptable level of inspection and planned maintenance for all of the other stations of a facility. This is exactly where undertaking a statistical failure analysis reveal one of its benefits for maintenance planners and managers.

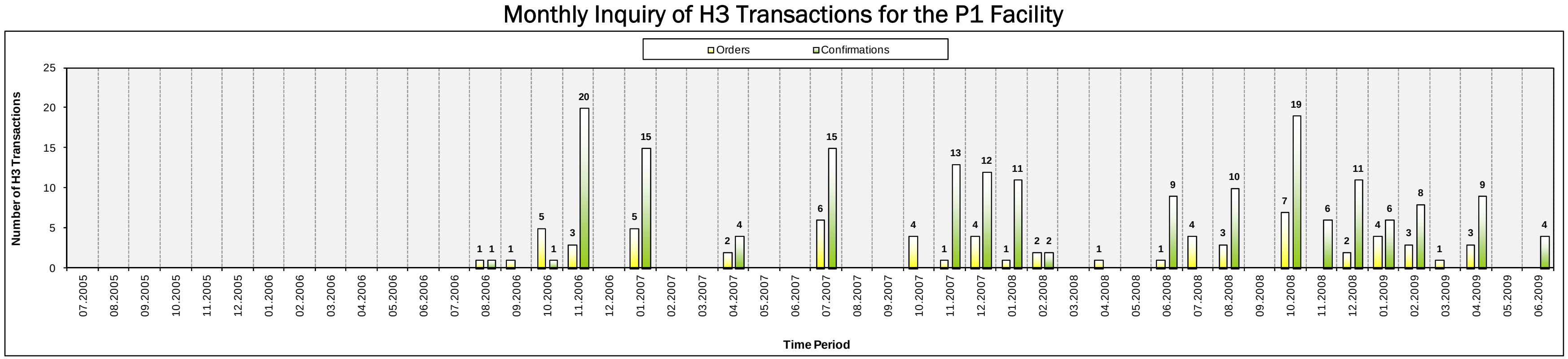


Figure 26 Number of different H3 transactions (i.e. orders and confirmations) per month for the P1 facility between 01.07.05 and 30.06.09

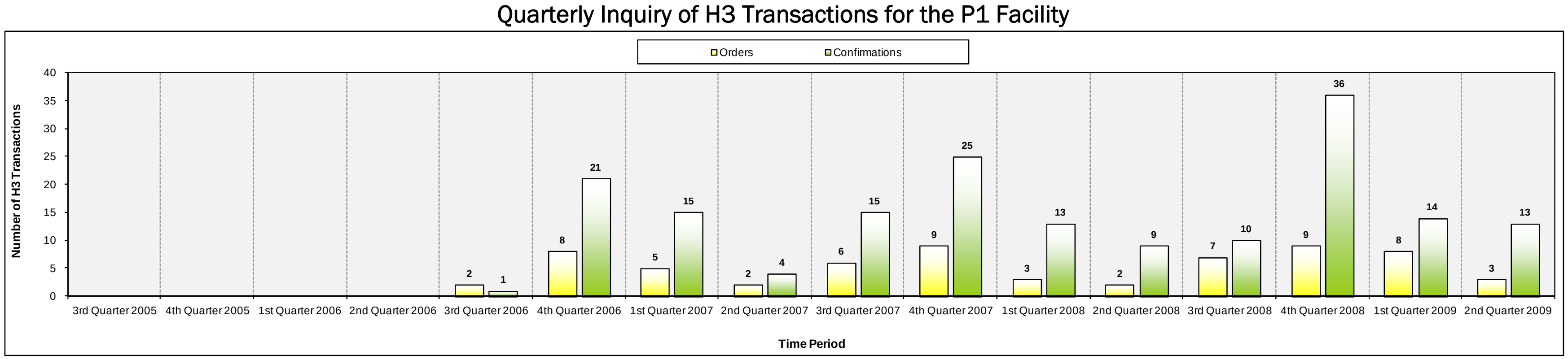


Figure 27 Number of different H3 transactions (i.e. orders and confirmations) per quarter-annum for the P1 facility between 01.07.05 and 30.06.09

5.2 Station Based Failure Analysis

This SFA section begins with precise scrutiny of available maintenance data related to the stations of P1 facility. The P1 facility consists of 28 different stations in the information system, each of which has a coded name by letters and numbers. Letter ‘A’ denotes the station for palettes washing machine, letter ‘V’ stands for preassembly stations and ‘GWM’ refers to the case washing machines. There are 18 main stations whose codes begin with the letter ‘S’. The two stations whose codes start with letter ‘H’ are hydraulic stations for which no failure data is available and hence were not included in the analysis. FB01 is the conveyer belt that goes round all the stations of the facility and finally the cabinet for central electronic control of the facility is named as EDV1 in the SAP system. All other failures that occur in the P1 facility but not at any of these specific stations are recorded under the name ‘General’.

As explained, number of major failures in a facility can be identified by the number of H1 orders placed in the SAP system. It is essential to underline that here the number of orders is taken into account rather than number of notifications as the H1 orders are placed in the information system being reviewed and evaluated by expert maintenance staff. Figure 28 indicates the number of major failures that has been occurred in each station of the P1 facility within the period of study that is totally 493 and on average 18 per station. Based on this figure, the three most failure critical stations of the P1 facility are S14, S01 and S02 with 61, 47 and 38 major failures accordingly. The three least failure critical stations of the P1 facility are S12A, S9 and S18A with only 1, 2 and 4 major failures respectively.

This is a simple but beneficial method to rank the most critical stations of a facility. The efforts of Heisler [262], Smith [576], Smith and Hawkins [573], and Wiegand et al. [660], [661] show how lean maintenance helps prioritizing facilities of a production plant regarding their importance based on the discussed factors. Undeniably, the lean concept can be perfectly used in categorization of damages and facilities. However, lean maintenance is incapable of prioritizing stations of a facility based on the same concept because of the fact that if any of the stations stops working, the facility itself halts. Thus, from lean perspective all of these stations are of equal importance to the plant. However, by implementing a simple statistical assessment as done above and throughout this section, one can easily identify and prioritize the most failure critical stations of a facility based on different factors which seek more technical care and require immediate focus of maintenance crew.

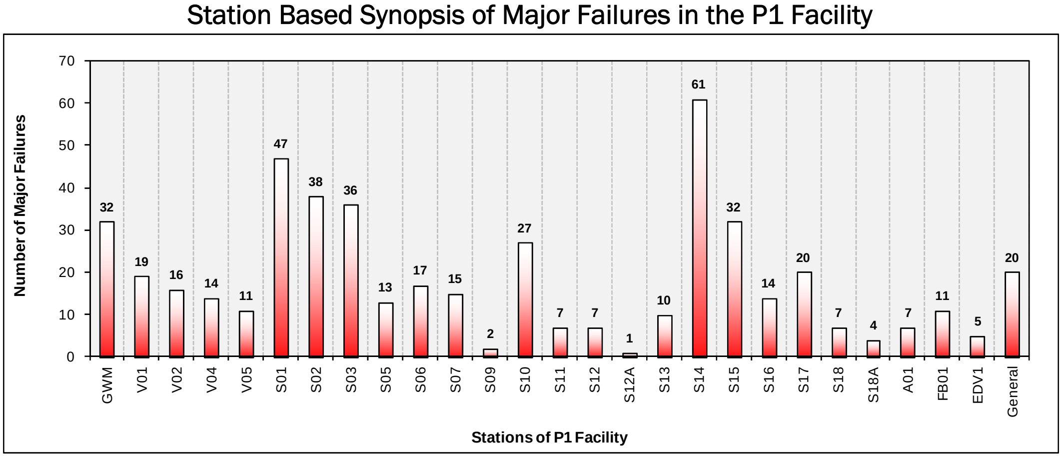


Figure 28 Station-based number of major failures in the P1 facility between 01.07.05 and 30.06.09

Number of minor failures in a facility can be identified by number of H2 notifications sent to the SAP system. It is important to express that here the number of notifications is taken into account rather than number of orders as H2 orders are only placed in the system if notifications are seen to have significant importance by maintenance staff. If an H2 notification is postponed to be placed as an order, it does not mean that there was no minor failure or disturbance, but just denotes lack of importance for maintenance personnel. Figure 29 shows the number of minor failures that has been occurred in each station of the P1 facility between 01.07.2005 and 30.06.2009 that is totally 1559 and on average 58 per station. According to this figure, the three most disturbing stations of the P1 facility are S01, S06 and S07 with 331, 174 and 170 minor failures respectively. The three least disturbing stations of the P1 facility are S05, EDV1 and S12 with only 7, 7 and 9 minor failures accordingly.

It is also notable that there are 134 minor failures or disturbances which have been classified under the term ‘General’. If these minor failures are more specifically defined and described by the workers in the plant or the technicians who fixed the problems, the accuracy of such analysis as the most failure critical or disturbing stations could be considerably increase. Besides, it has to be underlined that the scale of the occurrence of minor failures in stations like S01, S02, S06, S07, S014 and FB01 are quite larger than the one of other P1 stations. This requires further investigations by expert maintenance personnel. There are other analyses throughout this chapter, the result of which can definitely help finding the reasons behind such abnormalities. However, statistical failure analysis is a tool which has to be used in combination with other tools in maintenance framework in order to be entirely beneficial and effectively useful. Nevertheless, such a statistical failure analysis can be used for many purposes from machinery maintenance to spare part and inventory management, and even for performance evaluation of workers by human resources department.

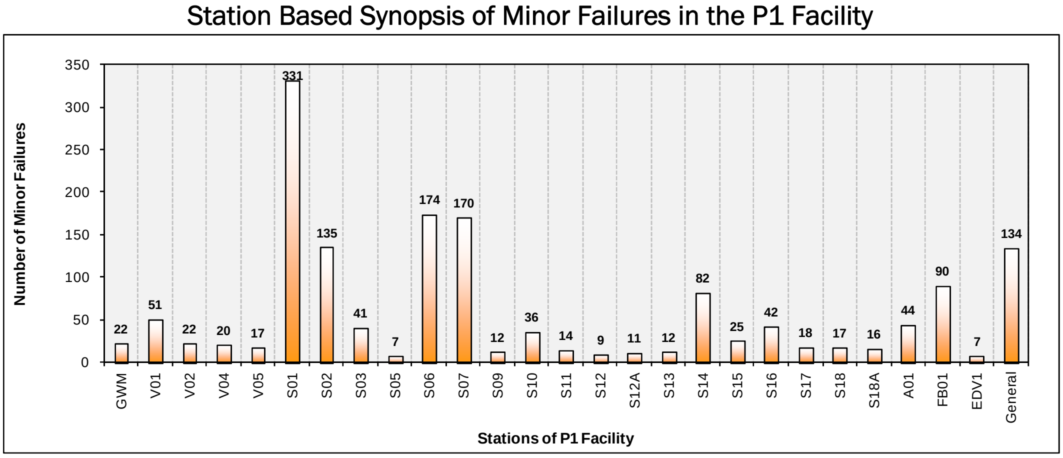


Figure 29 Station-based number of minor failures in the P1 facility between 01.07.05 and 30.06.09

Number of planned maintenance activities in a facility can be identified by number of H3 orders placed in the SAP system. These numbers can be also sketched based on the station in which the planned maintenance activities have taken place. This helps maintenance department to assess whether the planned maintenance activities have been effectively planned or not. Figure 30 shows the number of PM activities that has been carried out in different stations of the P1 facility. It can be easily seen that the most deliberately maintained stations of the P1 facility are V01, S14 and V02 having 16, 13 and 12 undertaken PM activities respectively. However, as shown in figure 28, the most failure critical stations of P1 facility through the same period of time were S14, S01 and S02. Here of course, comes the question if it was not better to have more PM activities specifically planned for these stations. Or, one can argue that the number of failures in the stations V01 and V02 has been lower in comparison as a consequence of the undertaken PM activities during these four successive years, i.e. from 01.07.2005 to 30.06.2009. This argument may hold true but it cannot be a reason to overlook the most failure critical or disturbing stations of the P1 facility.

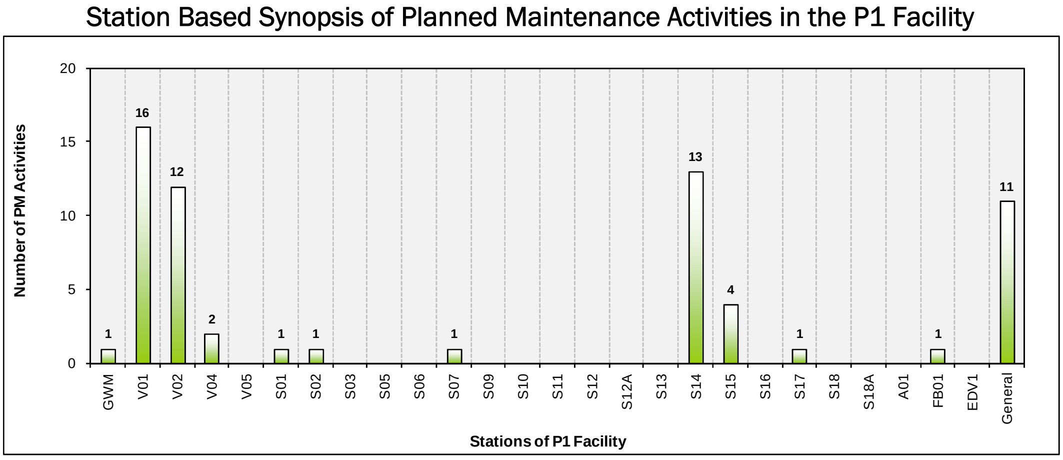


Figure 30 Station-based number of PM activities in the P1 facility between 01.07.05 and 30.06.09

Rather than maintaining a general view over the station based number of major and minor failures, it is possible to go one information layer underneath and to statistically analyze the overall number of problems associated with damaged equipment or machinery objects per station regardless of the category of the failure itself. As shown in figure 31, number of total damaged objects and thus occurred problems per station can be presented graphically. The total number of problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 is 2064, which counts for 76 problems per station on average. Clearly, this number may be different than just adding up number of major and minor failures as there might be more than one major objects requiring repair or change when a failure happened. As it can be expected, the most disturbing stations are the stations in which most of the equipment or machinery objects are damaged or failed. These most problematic stations are S01, S06 and S07 with 384, 199 and 198 problems accordingly.

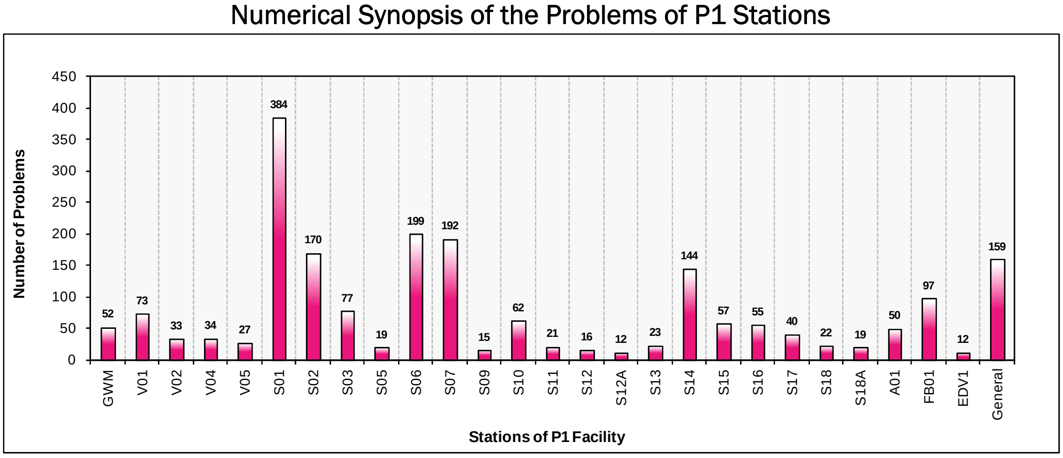


Figure 31 Number of recorded problems of the stations of P1 facility from 01.07.05 to 30.06.09

Figure 32 incorporates the philosophies and methodologies of ABC and Pareto analyses to illustrate the significancy or importance of different P1 stations according to the total number of occurred problems in four successive years [230], [263], [461], [555]. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total number of problems occurred in the P1 facility during the studied period. Such an approach helps visualizing the strongest and the weakest links.

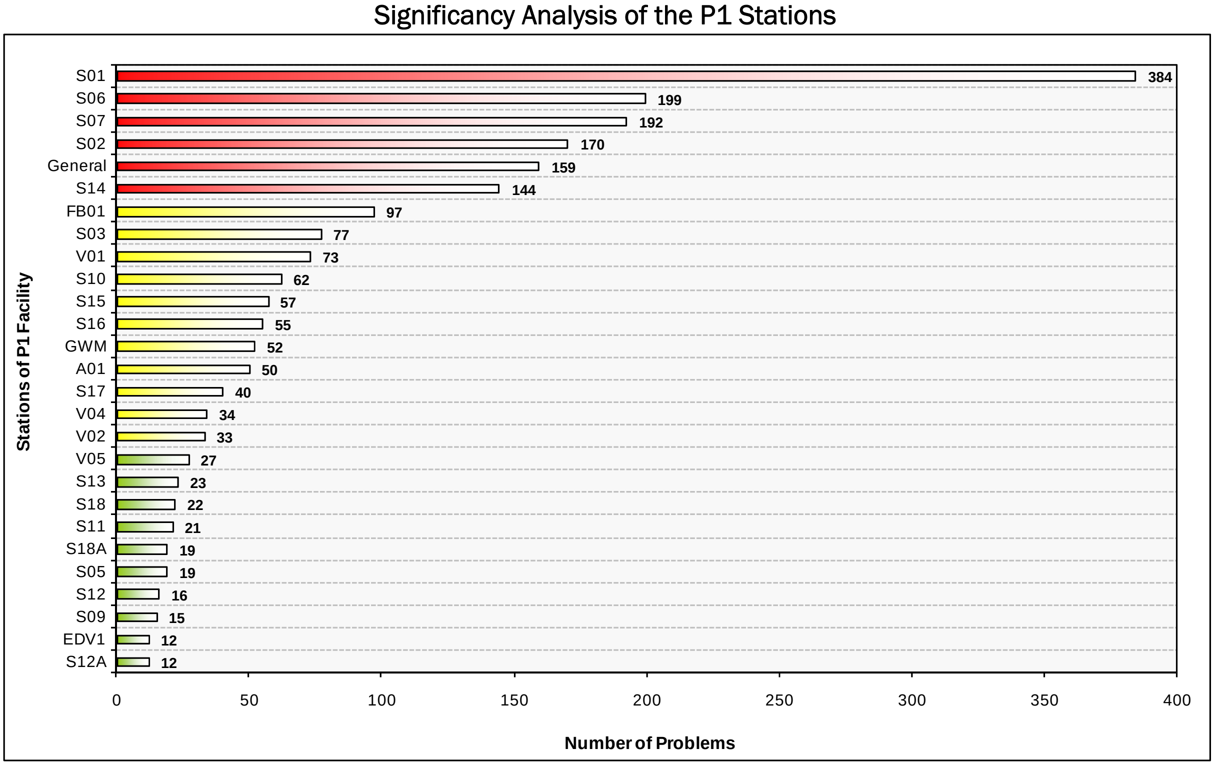


Figure 32 Number of recorded problems of the stations of P1 facility from 01.07.05 to 30.06.09; there is an approximate multi-colored classification of 60%, 30% and 10% of the total number of problems.

With a simple statistical analysis it is also possible to identify the most and the least plannedly maintainable stations in a facility. This is done by calculating the relative standard deviation or RSD (i.e. ratio of standard deviation of a population to its arithmetic average) for each station [485]. The station which has the smallest RSD is the most plannedly maintainable station as it has represented a steady failure behavior over time. On the other hand, the station with the largest RSD is the least plannedly maintainable station as it has shown an unstable failure behavior over time. Based on the monthly failure data from 01.07.2005 to 30.06.2009, S07 with an RSD of 48.1% has been the most and S12A and EDV1 with an RSD of 267.4% have been the least plannedly maintainable stations of the P1 facility.

Besides, using the same data the most and the least critical month of the year for each station can be identified; these are the months in which the stations have had the largest and smallest number of problems respectively. Such information is helpful for investigating root of problems or scheduling PM activities. To illustrate, for the station S07, the most critical months have been January and April with 5 occurred problems on average. For the same station the least critical month have been July and August with only 2 occurred problems on average. The same rule applies for the whole facility as well. The most critical month for the P1 facility has been September with 60 occurred problems on average and the least critical months are known to be May and December with 34 occurred problems on average. In a similar way, the most and the least critical quarters for P1 facility have been respectively the 1st quarter with 141 and the 2nd quarter with 116 occurred problems on average.

Another beneficial analysis involves examining the change of criticality of a facility's stations over time. It is vital to know if a station has remained the most problematic station for long period of time or there have been some efforts resulting in the status change of that station. Dividing the studied period from 01.07.2005 to 30.06.2009 into four annual cycles helps undertaking such an analysis. Figure 33 represents such results for the stations of the P1 facility. In the studied period of time and for four successive anni, the most problematic station of P1 facility has been the station S01 while the least problematic station has been changed from V04, FB01, S12 and eventually S11 in the last annum.

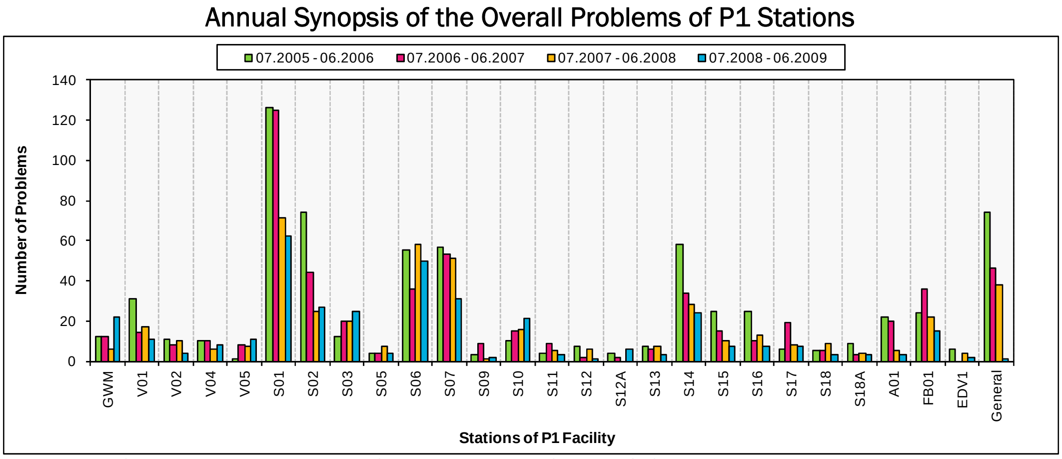


Figure 33 Number of recorded problems of the stations of the P1 facility in annual cycles within the time period from 01.07.05 to 30.06.09

In the SAP system of TRW-Schalke, problems are divided into two groups of electrical and mechanical. Therefore, a similar analysis and prioritization can be done taking into account these two problem categories. In this way, it is possible to easily see the nature of the occurred problems in a station of a particular facility. Between 01.07.2005 and 30.06.2009, the total number of electrical problems is 502 while this number is 1562 for mechanical problems in the P1 facility. And, the average numbers of electrical and mechanical problems are 19 and 58 per station. As it can be seen from figure 34, the most electrically problematic stations are S14, S02 and S07, and S01 with according 46, 37, and 36 electrical problems. In the same period of time, the most mechanically problematic stations are again S01, S06 and S07 with 349, 168 and 155 mechanical problems respectively. Building up such a station ranking with respect to the problem type is quite useful in optimizing the utilization of maintenance resources and scheduling the planned maintenance activities. To illustrate, for most electrically problematic stations, PM activities can be scheduled to be undertaken by electrical technicians while utilizing mechanical technicians for the planned maintenance or routine inspection of the most mechanically problematic stations.

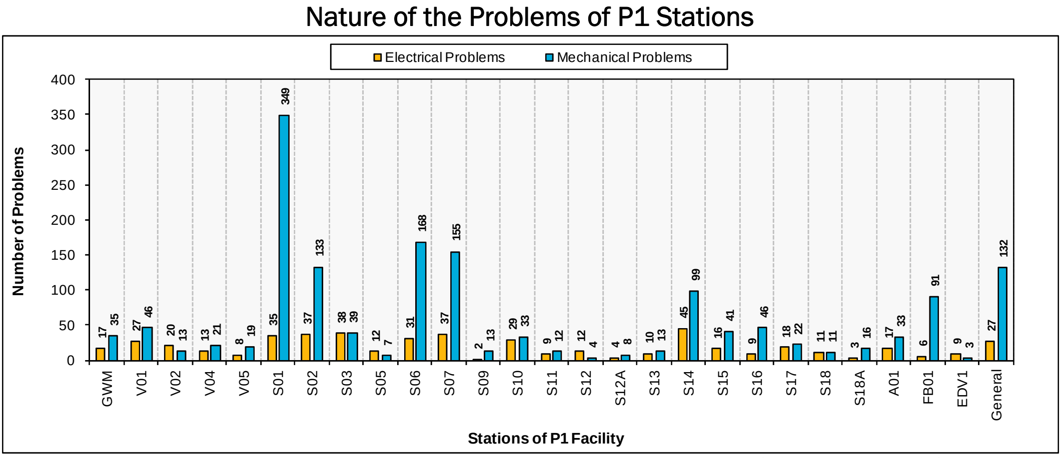


Figure 34 Number of electrical and mechanical problems in the stations of P1 facility from 01.07.05 to 30.06.09

Figures 35 and 36 illustrate the numerical variation of occurred electrical and mechanical problems in the stations of the P1 facility over four successive anni. While on average, these numbers have been trimmed down in the P1 facility, in particular stations like S10 and V05 they show considerable increase in the last annum.

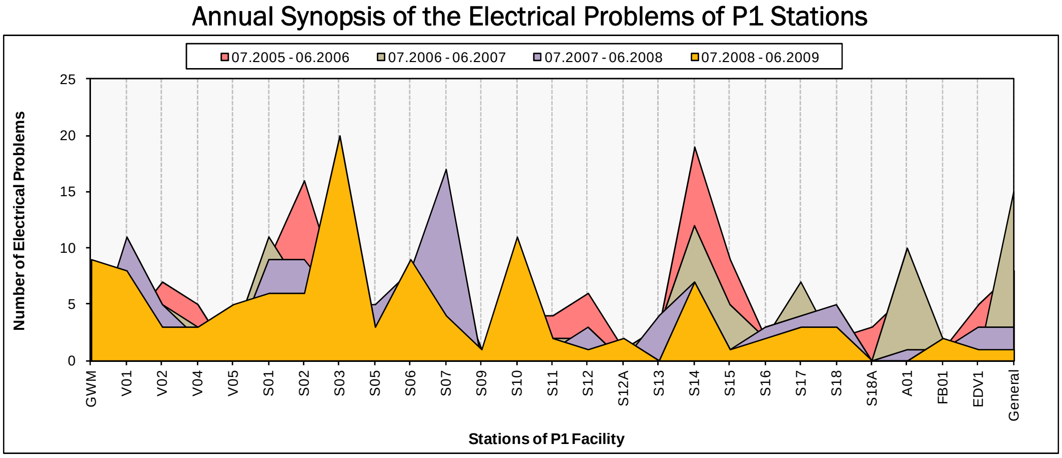


Figure 35 Numerical variation of electrical problems of the stations of P1 facility from 01.07.05 to 30.06.09

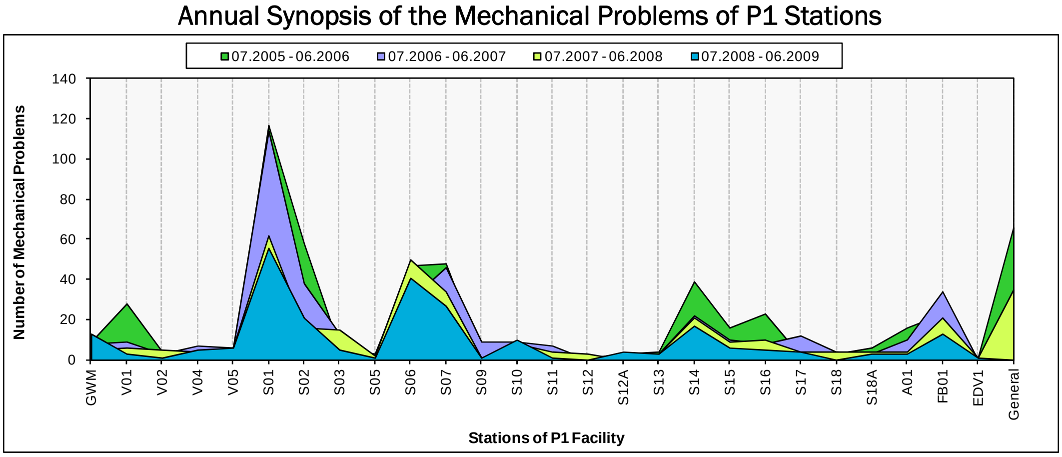


Figure 36 Numerical variation of mechanical problems of the stations of P1 facility from 01.07.05 to 30.06.09

Based on the same methodology used to spot the plannedly maintainable stations, it is possible to identify which stations are the most and least electrically or mechanically maintainable by the PM concept. In this framework, Stations S06 and S18A have been found to be the most and the least plannedly maintainable stations with respective 16% and 200% RSD. Stations S13 and S12 have been found to be the most and the least plannedly maintainable stations with respective 15.4% and 141.4% RSD. These numbers unlike the ones calculated for the P1 facility in general are on annual basis. The reliability this information can be extremely increased if the RSD is calculated on monthly basis.

In the SAP system of TRW-Schalke, objects have been split in two major groups of machinery and equipment objects. The number of object based problems per station can then be plotted graphically based on the mentioned two different groups of objects. Figure 37 indicates that out of 2064 object based problems in the P1 facility within the studied period, 1216 are related to the faulty or damaged machinery objects and 848 are related to the faulty or damaged equipment objects. Making an average over total number of stations, these numbers account for 45 damaged machinery objects and 31 damaged equipment objects per station. Taking into account the number damaged machinery objects, the most faultfinding stations are S01, S14 and S02 with 161, 131 and 84 damaged machinery parts. And considering the number of faulty equipment objects, the most faultfinding stations are S01, S07 and S06 with 233, 134 and 126 damaged equipment objects.

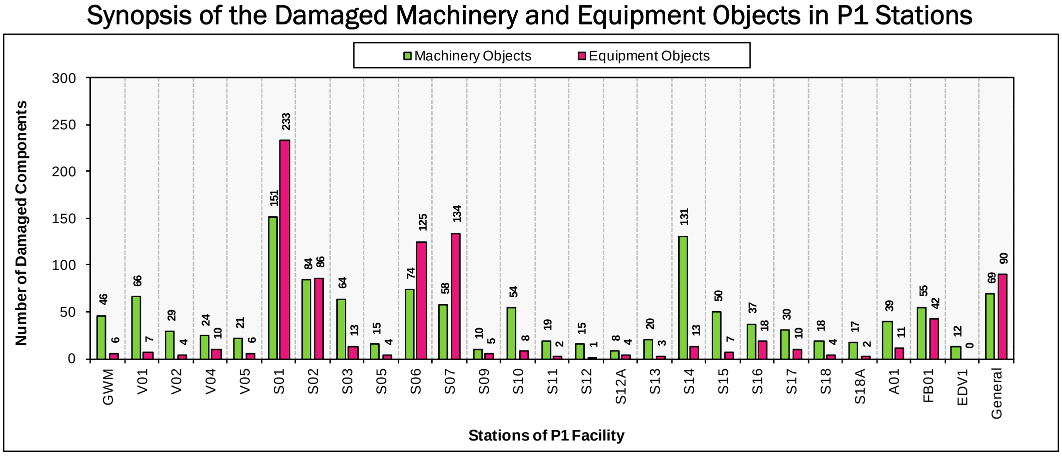


Figure 37 Number of problems related to machinery and equipment objects in different stations of P1 facility from 01.07.05 to 30.06.09

Using the available failure data, the variation of number of problems with respect to the quarter in which they occurred can be displayed. This information is helpful in discovering the failure behavior of stations of a facility in different quarters of a year. Figure 38 shows such a variation for the stations of P1 facility. For example, station S01 seems to be more problematic in the 4th quarter of a year in comparison with the 2nd quarter. Knowing this can provide the maintenance planners and technicians with essential information.

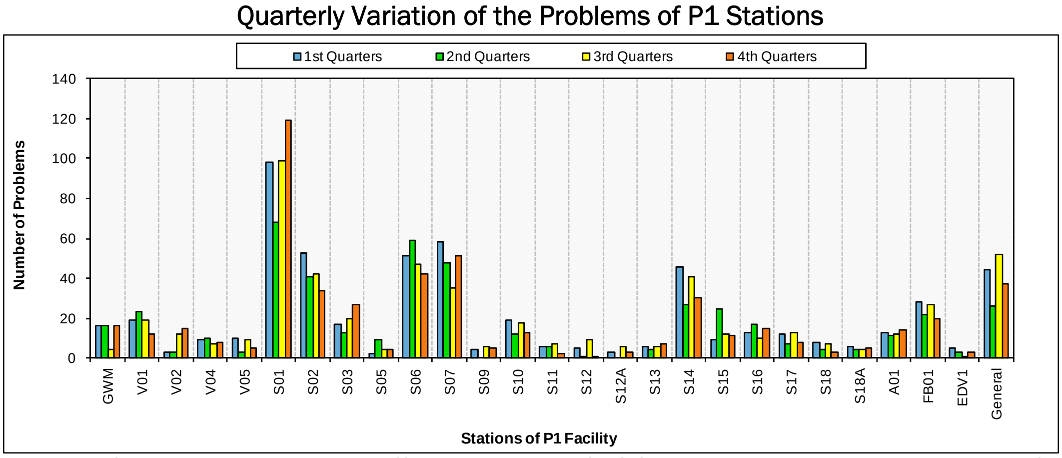


Figure 38 Amount of recorded problems in different stations of P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

Maintenance planners can schedule the maintenance activities somehow to heal the critical status of S01 in the 4th quarter and the technician can investigate the root of such an incident. From management perspective, one should arrange the availability of resources required to fix the problems in S01 station. The resources may range from particular spare parts to the technicians who are more familiar with this specific station and the machinery used there. Depending on the situation and preferred degree of accuracy, the timely variation of number of problems in a facility can be presented in a monthly format as it is shown in the next figure for the P1 facility.

The below figure can be used to simply determine and monitor the critical months for each station of the P1 facility. As an example, the most critical month of a year for station S14 can be easily identified as March. As it has been mentioned before, such information can be employed for planning and scheduling resources to fix the problems in time or even prevent them, as well as, for investigating the root cause of some time-based incidents.

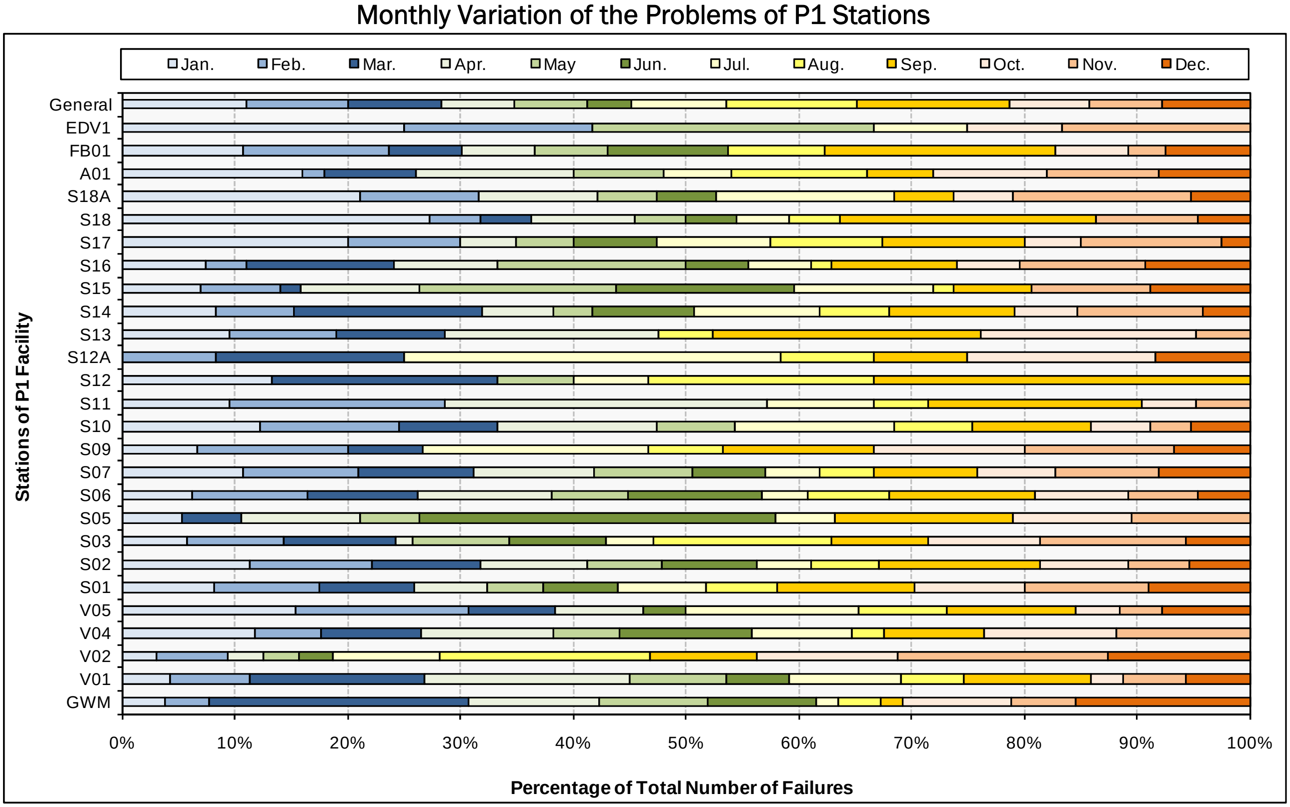


Figure 39 Percentage of problems in different stations of P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

In addition to what has been shown graphically, it is beneficial to identify different machinery objects which have been mostly failed or damaged in each station of the P1 facility. This is done and tabulated in a way showing the most critical machinery object in each station. Indeed, such information is quite essential as it can be used by maintenance department for different purposes. For instance, knowing that historically valves are the most frequently damaged machinery objects in the station S10, when a notification of failure comes as a mechanical problem, the technician can immediately take a valve which is particularly used in the station S10 as it is very probable that the valve is the faulty part.

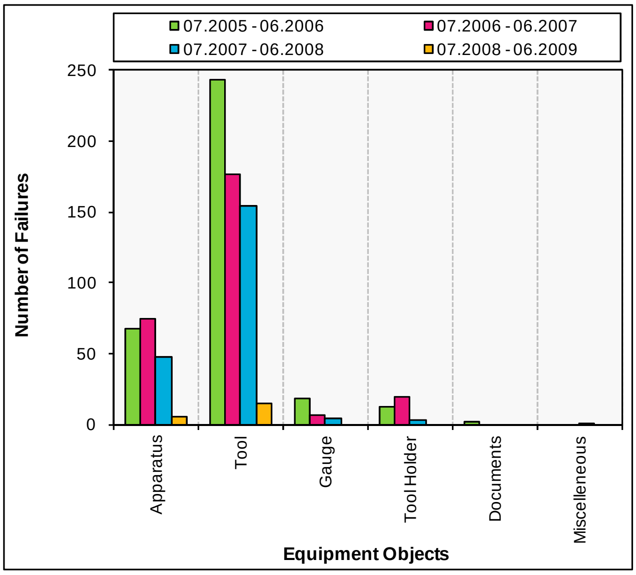
Moreover, from the spare part and inventory management perspective, knowing the most frequently failed or damaged machinery objects means being able to keep the inventory level at an optimum level having all the most critical parts available. Such information and the resultant benefits will definitely help to lessen maintenance and repair time which is indeed making more money. Clearly, such an analysis can be done for a facility or a plant in general, but that would be more useful in spare part and inventory management rather than the maintenance activities themselves. This is also shown more in details in coming pages. Table 6, in the next page, indicates the most failure-critical machinery object(s) in the station of the P1 facility in the studied period of time.

Table 6 The most failure-critical machinery object(s) in each station of the P1 facility from 01.07.05 to 30.06.09

Station	Total No. of Faulty Machinery Object	Machinery Object Code(No. Failures)	Most Failure-Critical Machinery Object(s)	
			Code	Object
GWM	46	0001(**1**),0003(**8**),0006(**1**),0007(**1**),0009(**1**),0011(**2**),0012(**1**),0013(**1**),0014(**1**),0011(**1**),0017(**2**),0018(**2**),0020(**1**),0022(**2**),0023(**1**),0024(**1**),0026(**4**),0027(**8**),0028(**1**),0037(**6**)	0003	Motor
V01	66	0007(**3**),0009(**3**),0010(**11**),0011(**3**),0014(**5**),0015(**7**),0016(**6**),0017(**6**),0019(**2**),0020(**5**),0021(**1**),0023(**7**),0027(**3**),0037(**4**)	0010	Hydraulic Cabinet
V02	29	0009(**3**),0010(**1**),0011(**1**),0014(**1**),0015(**2**),0019(**2**),0020(**1**),0021(**1**),0023(**9**),0027(**2**),0035(**1**),0037(**1**)	0023	Measuring Sensor
V04	24	0001(**1**),0008(**2**),0009(**2**),0011(**2**),0012(**1**),0016(**1**),0018(**1**),0019(**1**),0020(**3**),0023(**1**),0026(**2**),0027(**4**),0037(**3**)	0027	Switching/Control Element
V05	21	0003(**2**),0011(**2**),0015(**1**),0016(**4**),0017(**4**),0023(**2**),0027(**5**),0034(**1**)	0027	Switching/Control Element
S01	151	0001(**2**),0003(**1**),0006(**5**),0007(**3**),0008(**3**),0011(**10**),0012(**1**),0013(**6**),0014(**5**),0015(**12**),0016(**14**),0017(**10**),0018(**6**),0019(**8**),0021(**1**),0026(**2**),0027(**10**),0037(**52**)	0037	Miscelleneous
S02	84	0001(**1**),0003(**2**),0006(**2**),0007(**1**),0008(**4**),0011(**4**),0012(**3**),0013(**2**),0014(**2**),0015(**3**),0016(**7**),0017(**13**),0018(**3**),0019(**3**),0020(**1**),0023(**1**),0024(**1**),0027(**4**),0037(**2**)	0017	Switch/Button
S03	64	0003(**2**),0006(**1**),0009(**1**),0010(**2**),0011(**1**),0012(**3**),0014(**7**),0015(**6**),0016(**7**),0017(**1**),0018(**4**),0019(**1**),0020(**6**),0023(**6**),0026(**1**),0027(**9**),0031(**1**),0037(**5**)	0027	Switching/Control Element
S05	15	0015(**1**),0016(**6**),0017(**1**),0023(**4**),0027(**2**),0034(**1**)	0016	Cable/Wire
S06	74	0011(**1**),0013(**1**),0014(**2**),0016(**26**),0017(**3**),0018(**1**),0019(**2**),0023(**1**),0037(**37**)	0016	Cable/Wire
S07	58	0002(**1**),0009(**1**),0015(**2**),0016(**24**),0019(**4**),0020(**1**),0023(**1**),0027(**4**),0030(**1**),0037(**19**)	0016	Cable/Wire
S09	10	0011(**1**),0014(**1**),0016(**1**),0018(**1**),0019(**2**),0027(**3**),0028(**1**)	0027	Switching/Control Element
S10	54	0007(**3**),0010(**2**),0014(**11**),0015(**9**),0016(**4**),0017(**1**),0019(**3**),0023(**6**),0027(**7**),0034(**2**),0037(**6**)	0014	Valve
S11	19	0007(**2**),0009(**1**),0015(**3**),0017(**2**),0019(**2**),0023(**2**),0024(**2**),0025(**1**),0027(**2**),0023(**2**)	0015	Cylinder
S12	15	0008(**4**),0011(**1**),0013(**1**),0016(**3**),0017(**5**),0019(**1**)	0017	Switch/Button
S12A	8	0006(**1**),0015(**1**),0017(**3**),0019(**1**),0027(**1**),0028(**1**)	0017	Switch/Button
S13	20	0002(**2**),0006(**1**),0009(**2**),0012(**1**),0014(**3**),0015(**3**),0016(**1**),0018(**1**),0023(**2**),0026(**1**),0027(**3**)	0014,0015,0027	Valve,Cylinder,Switching/Control Element
S14	131	0003(**1**),0006(**2**),0007(**4**),0009(**4**),0010(**7**),0011(**4**),0012(**2**),0014(**12**),0015(**8**),0016(**15**),0017(**3**),0018(**1**),0019(**4**),0023(**30**),0024(**21**),0026(**1**),0027(**5**),0030(**2**),0034(**1**),0035(**2**),0037(**2**)	0023	Measuring Sensor
S15	50	0001(**1**),0003(**6**),0007(**23**),0009(**1**),0012(**1**),0015(**2**),0016(**2**),0019(**3**),0023(**5**),0026(**3**),0035(**1**),0037(**2**)	0007	Pump
S16	37	0011(**3**),0012(**1**),0014(**12**),0015(**2**),0016(**8**),0017(**3**),0018(**1**),0023(**1**),0027(**3**),0028(**1**),0034(**1**),0037(**1**)	0016	Cable/Wire
S17	30	0003(**2**),0006(**2**),0009(**2**),0011(**1**),0015(**5**),0016(**1**),0017(**2**),0018(**4**),0019(**1**),0023(**1**),0026(**3**),0027(**5**),0034(**1**)	0015,0027	Cylinder-Switching/Control Element
S18	18	0014(**1**),0016(**5**),0017(**4**),0018(**1**),0022(**1**),0023(**1**),0027(**4**),0037(**1**)	0016	Cable/Wire
S18A	17	0006(**1**),0010(**2**),0011(**1**),0012(**1**),0013(**1**),0015(**3**),0016(**2**),0017(**1**),0018(**1**),0019(**1**),0024(**1**),0037(**2**)	0015	Cylinder
A01	39	0003(**2**),0011(**5**),0013(**7**),0016(**1**),0017(**2**),0018(**4**),0026(**8**),0027(**10**)	0027	Switching/Control Element
FB01	55	0003(**1**),0008(**1**),0009(**2**),0013(**31**),0014(**1**),0015(**3**),0017(**1**),0026(**4**),0027(**3**),0037(**8**)	0013	Conveyer Belt
EDV1	12	0016(**1**),0019(**1**),0022(**3**),0027(**5**),0034(**1**),0037(**1**)	0027	Switching/Control Element
General	69	0001(**1**),0003(**2**),0007(**2**),0010(**3**),0011(**10**),0013(**1**),0014(**6**),0015(**4**),0016(**5**),0017(**7**),0019(**1**),0020(**1**),0023(**7**),0024(**1**),0025(**1**),0026(**1**),0027(**12**),0034(**1**),0037(**3**)	0027	Switching/Control Element

5.3 Object Based Failure Analysis

Object based failure analysis is very useful in identifying the most failure critical objects in a facility or in a plant. These objects are basically the ones which are more frequently failed or damaged. Number of object based problems can be plotted per object or part that has been failed in a facility. As previously mentioned the objects or parts are divided into two groups in the SAP system of TRW-Schalke, equipment objects and machinery objects. Figure 40 presents the change of criticality of different equipment objects in the P1 facility in four successive anni from 01.07.2005 to 30.06.2009. The below figures show that for four successive anni, tool and apparatus have been the first and the second critical objects among all the listed categories of equipment objects with respective 589 and 194 failures. Obviously, classification of different equipment objects directly affects quality of the undertaken statistical analysis and its output information. The more optimally detailed are the categories of the equipment objects, the higher is the quality and usefulness of the output of the analysis. The current list of equipment objects does not seem to be optimally made. There are a few very general categories, the differences of which have not been clearly identified.


Annual Synopsis of the Damaged Equipment Objects in P1 Facility

It is vital to know if an equipment object has remained the most critical object for long a period of time or there have been some efforts resulting in the status change of that equipment object. Dividing the studied period from 01.07.2005 to 30.06.2009 into four annual cycles helps undertaking such an analysis.

As the graph on the left clearly indicates, the most critical equipment object in the P1 facility has been the 'tool' for four successive anni. This situation has been the same for 'apparatus' as the second critical equipment object on the list. Nevertheless, the number of damaged equipment objects in these two categories has decreased annually. Moreover, the decrease of the number of damaged equipment objects has been quite considerable in the last annum from 01.07.2008 to 30.06.2009.

The usefulness of the output of such an analysis can only be increased, if the classification of different equipment objects is made optimally detailed.

Figure 40 Number of damaged equipment objects in the P1 facility in annual cycles from 01.07.05 to 30.06.09

Figure 41 gets use of the philosophies and methodologies of ABC and Pareto analyses to illustrate the significancy or importance of different equipment objects. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total number damaged equipment objects during the studied period. However, it has to be underlined that the equipment objects are so generally classified that having such information would not be very useful unless a better list was made.

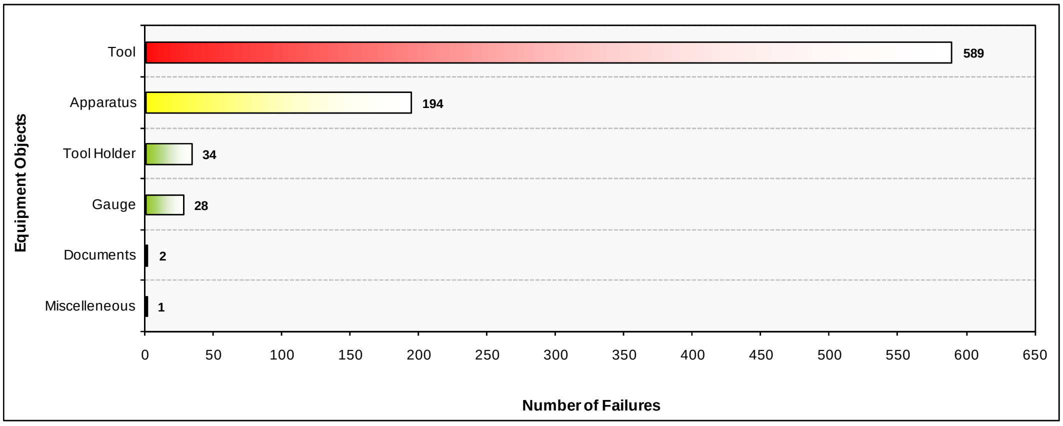
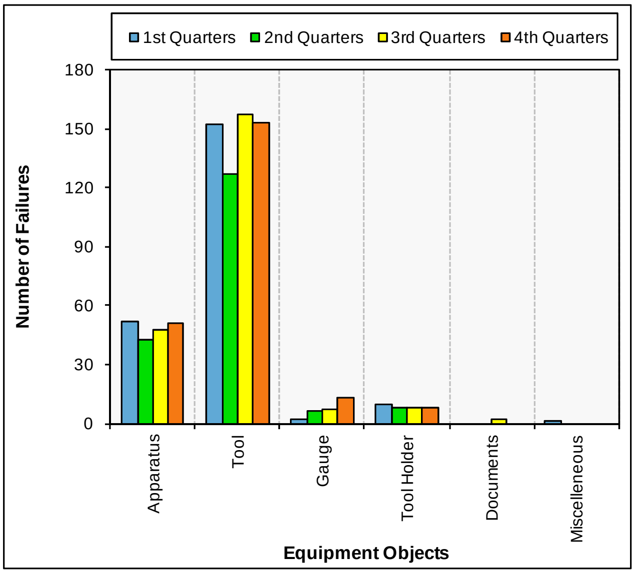

Significancy Analysis of the Damaged Equipment Objects in P1 Facility

Figure 41 Number of damaged equipment objects in the P1 facility from 01.07.05 to 30.06.09; there is an approximate multi-colored classification of 60%, 30% and 10% of the total number of damaged objects.

As done before, using the relative standard deviation it is possible to identify the most and the least plannedly maintainable equipment objects with the according lowest and highest RSD. Using this methodology and based on the available monthly data, the most plannedly maintainable equipment object is tool and the least plannedly maintainable one is documents with respective 67.9% and 692.8% RSD. The lowest and highest RSDs also refer to the objects which have to be always kept in inventory and the ones which would be better ordered at the time of failure if their total number of failure for a definite period of time is not considerable. Moreover, the most and the least critical month of the year for the whole and each of the equipment objects can be determined; these are the months in which the equipment objects have had the largest and smallest number of failures respectively. To illustrate, for the equipment object 'tool', the most critical month has been September with 17 failures on average. For the same object the least critical month has been May with only 9 failures on average.

The most and least critical month for the equipment objects, on the whole, have been September and August with respective 25 and 13 failures on average. In a similar way the most critical quarters for equipment objects have been the 3rd and 4th quarters with 56 failures on average and the least critical quarter of the year is the 2nd quarter with 46 failures on average. Figure 42 shows the variation of number of damaged equipment objects with respect to the quarter in which their failure occurs. Depending on the situation and preferred degree of accuracy, the timely variation of number of damaged equipment objects can be plotted in a monthly format as it is shown in figure 43. The below figure can be used to simply monitor the critical months for various equipment objects. As an example, the most critical month of a year for tool holder can be easily identified as September.

Quarterly Variation of the Damaged Equipment Objects in P1 Facility



Plotting variation of number of damaged equipment objects with the quarter of failure is helpful in determining these objects' failure behavior in different quarters of a year.

The graph on the left not only noticeably presents the most critical equipment object in the P1 facility as the 'tool', but also it indicates that the most critical quarter for this equipment object is the 3rd and least critical one is the 2nd quarter. These vary for the 'gauge' as it has the highest number of failures in the 4th quarter and the lowest in the 1st quarter.

Knowing this can provide the maintenance planners and technicians, and inventory managers with indispensable information. Maintenance planners can schedule the maintenance or replacement of frequently failed equipment objects. Maintenance technicians can investigate the reasons behind the high rates of equipment failure. And, inventory managers become able to optimize and control their inventory level.

Figure 42 Number of damaged equipment objects in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

Monthly Variation of the Damaged Equipment Objects in P1 Facility

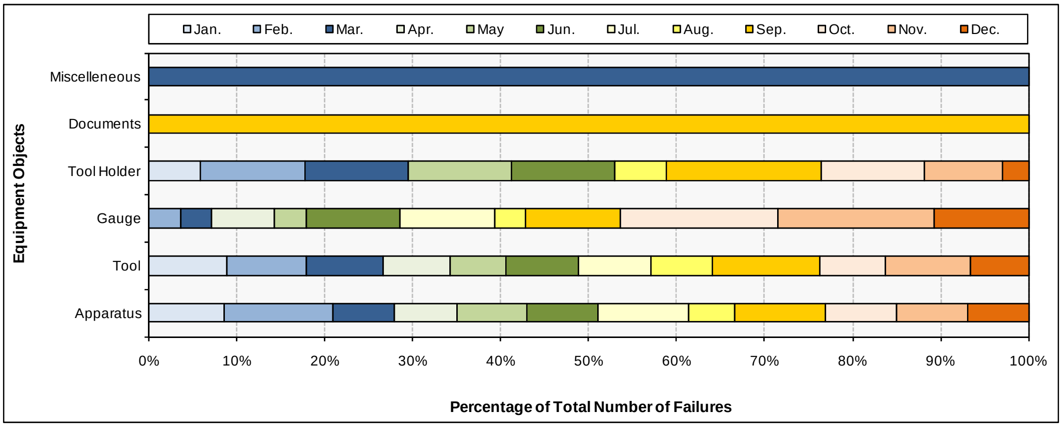


Figure 43 Percentage of damaged equipment objects in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

The same analyses can be done for the machinery objects in the P1 facility. Figure 44 shows the change of criticality of different machinery objects in the P1 facility in four successive anni from 01.07.2005 to 30.06.2009. Figure 45, on the other hand, illustrates the significancy or importance of different machinery objects. This provides more precise and useful results as the list of machinery objects has been more comprehensively made in comparison with the list of equipment objects.

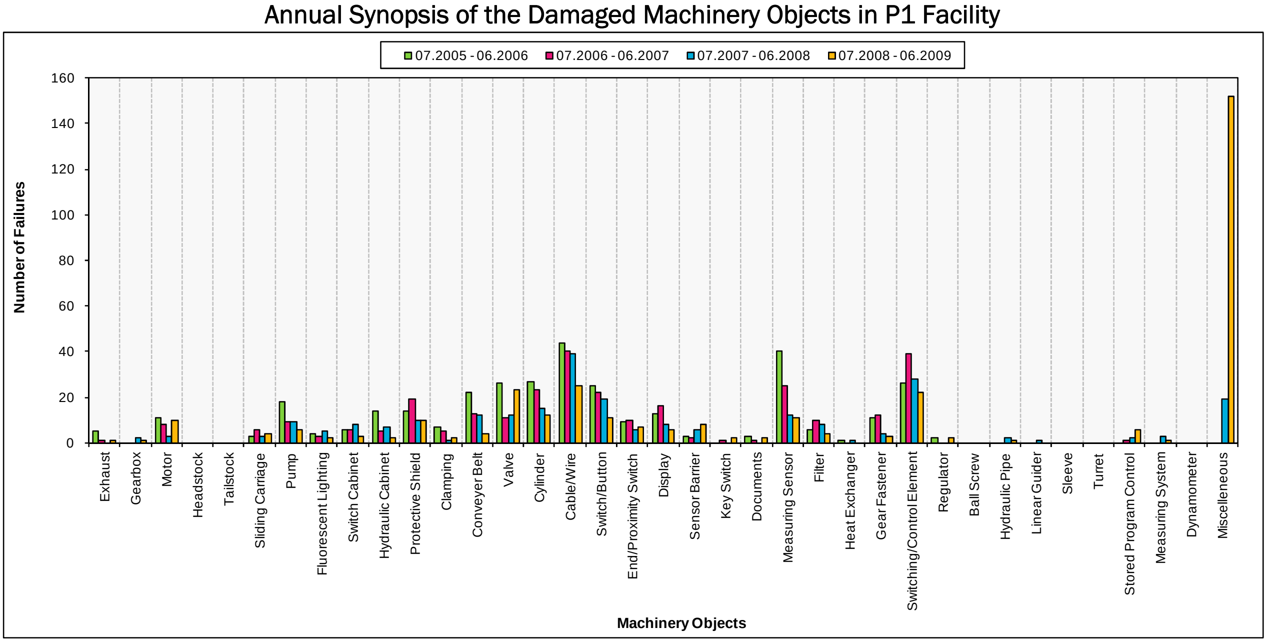


Figure 44 Number of damaged machinery objects in the P1 facility in annual cycles from 01.07.05 to 30.06.09

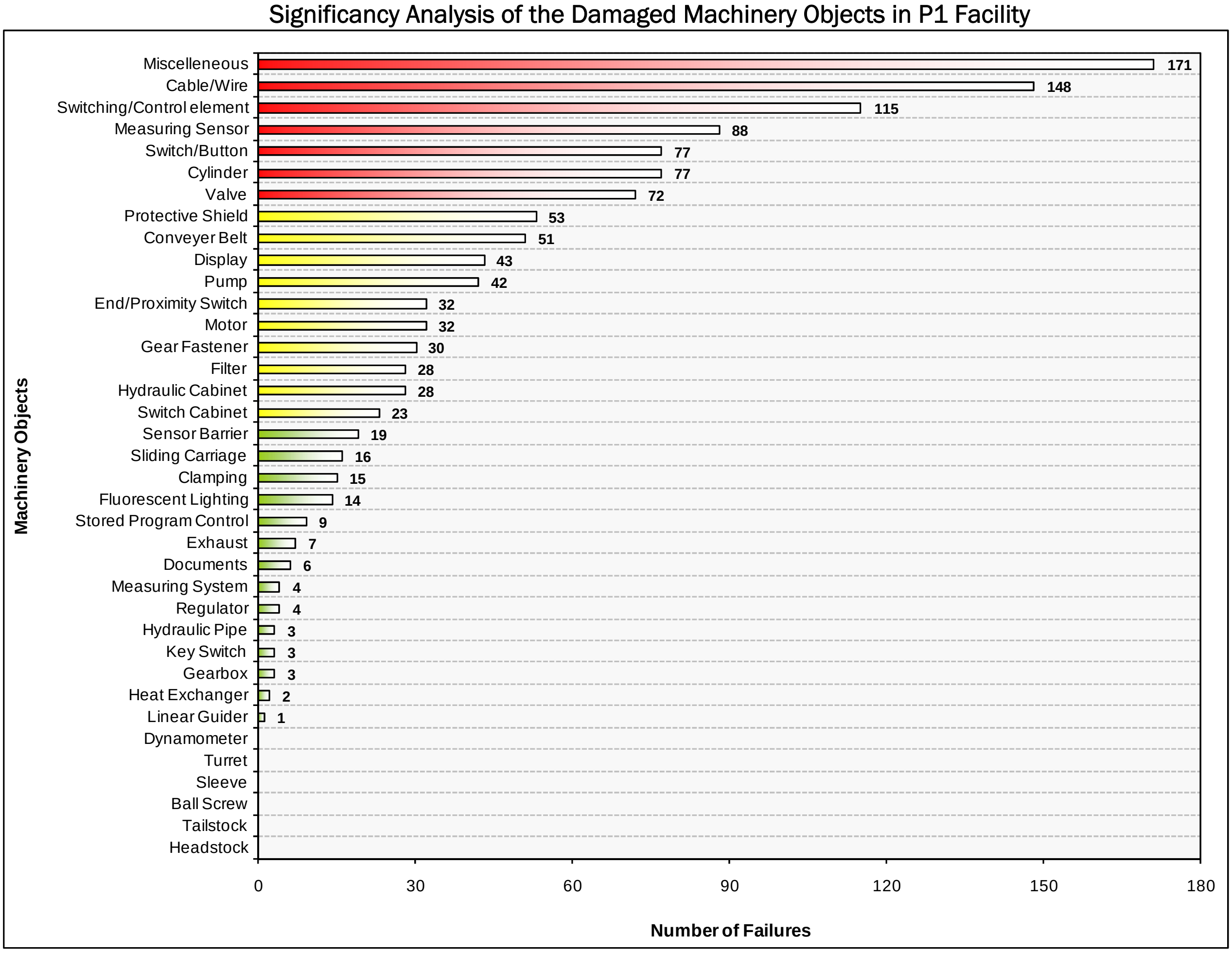


Figure 45 Number of damaged machinery objects in the P1 facility from 01.07.05 to 30.06.09; there is an approximate multi-colored classification of 60%, 30% and 10% of the total number of damaged objects.

Between 01.07.2005 and 30.06.2009 the most critical machinery objects were recorded as cable/wire, switching/controlling element and measuring sensor with total number of 148, 115 and 88 failures respectively. Within the same period of time the least critical machinery objects have been linear guider, heat exchanger and gearbox with total number of 1, 2 and 3 failures accordingly (excluding headstock, tailstock, ball screw, sleeve, turret and dynamometer which had no failure in the P1 facility in during the studied period). It is essential to underline that knowing the most frequently damaged or the most critical machinery parts in facility helps identifying the most suitable condition monitoring technique or nondestructive test as long as the information about the related problems or failures are also available. In addition, such information is quite handy for spare part management. The inventory managers can optimize and control their inventory level taking to account the type and number of the most frequently damaged machinery objects. As the case of equipment objects, the better classification of different machinery objects positively affects the quality of the undertaken statistical analysis and hence the resultant information. The more optimally detailed are the categories of the machinery objects, the higher is the quality and usefulness of the output of the analysis.

Using the relative standard deviation methodology and based on the data in hand, it is possible to determine the most and the least plannedly maintainable machinery objects with the respective lowest and highest RSD. In the P1 facility, the most plannedly maintainable machinery object is cable/wire and the least plannedly maintainable one is linear guider with respective 61.3% and 692.8% RSD. The lowest and highest RSDs also refer to the objects which have to be always kept in inventory and the ones which would be better ordered at the time of failure if their total number of failure for a definite period of time is not considerable. The most and the least critical month of the year for the whole and each of the machinery objects can be identified, being the months in which the machinery objects have had the largest and smallest number of failures respectively. For instance, for 'cable/wire', the most critical month has been October with 5 failures on average. For the same object the least critical month has been January with only 2 failures on average. Considering the whole machinery objects, the most and least critical month have been September and July with respective 36 and 19 failures on average. The most critical quarters for machinery objects have been the 1st quarter with 88 failures on average and the least critical quarters of the year are the 3rd and 4th quarters with 70 failures on average.

Figure 46 shows the variation of number of damaged machinery objects with respect to the quarter in which their failure occurs. As shown for equipment objects, depending on the situation and favored precision degree, the timely variation of number of damaged machinery objects can be drawn on a monthly basis. Figure 47, in the next page, represents such a monthly variation and can be employed to simply show the critical months for various machinery objects. As an example, the most critical month of a year for switching/control elements can be easily identified as January.

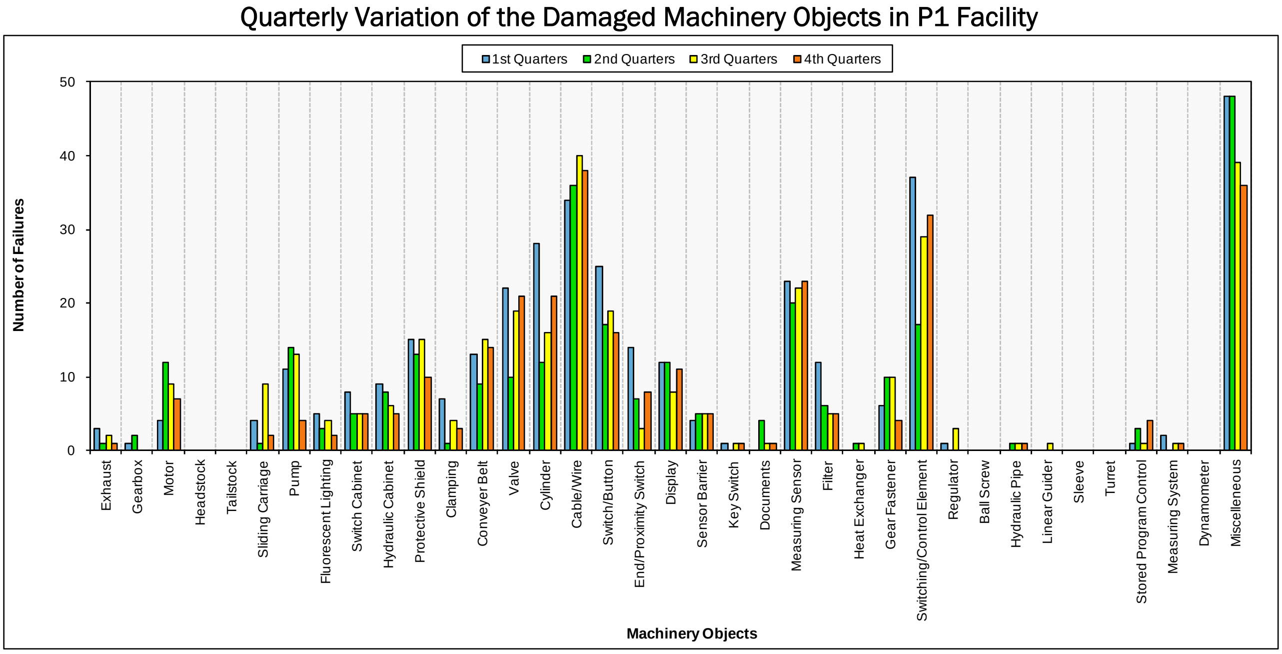


Figure 46 Number of damaged machinery objects in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

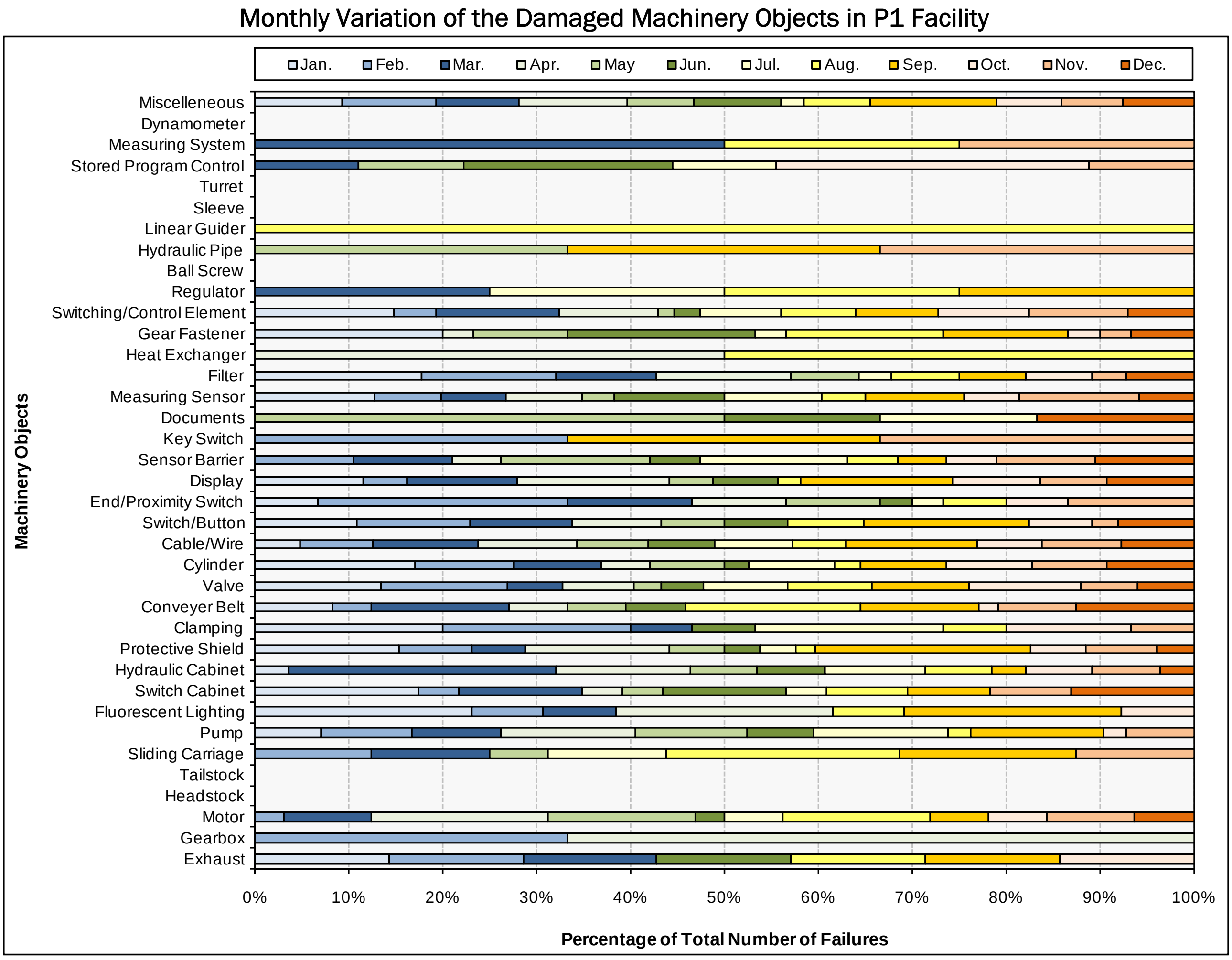


Figure 47 Percentage of damaged machinery objects in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

Next vital information which can be retrieved from the P1 facility's failure data is the degree of importance of each equipment or machinery object for particular stations of facility. This is undertaken by determining the number of times each object has been damaged or failed in a station. The station, in which this number is the largest, is the one that has been mostly vitiated (i.e. made ineffective or out of order) by that particular object. Tables 7 and 8 indicate the most vitiated stations of the P1 facility by all categorized equipment and machinery objects. This information is more statistically valuable as it reveals the correlation between two physical entities, the objects and the stations. For example, it can be investigated why gauges fail more in S14 or motors in GWM rather than the other P1 stations, if it is a technical matter or an operators fault.

Table 7 The most vitiated stations of P1 facility by damaged equipment objects from 01.07.05 to 30.06.09

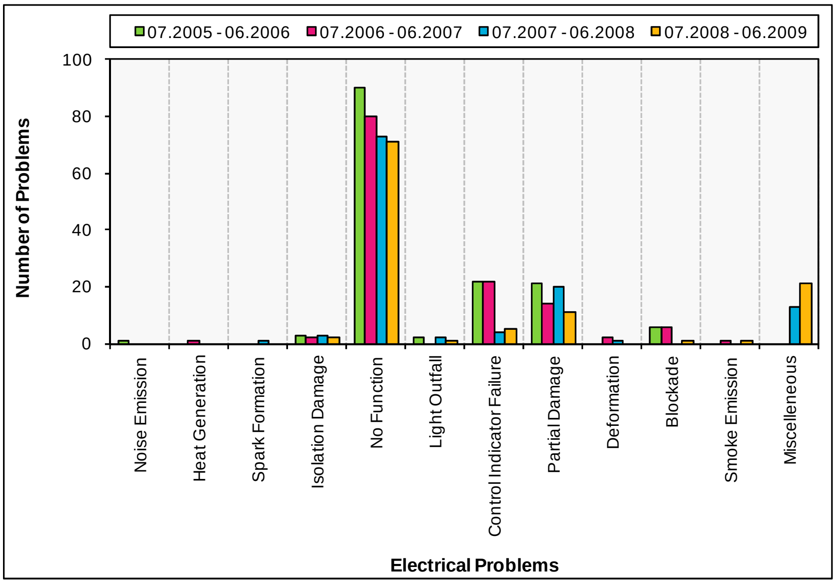
Code	Equipment Object	Total No. of Failures	Station(No. Failures)	Most Vitiated Station
				Code
B001	Apparatus	194	GWM(6),V01(4),V02(1),V04(7),V05(2),S01(22),S02(14),S03(5),S05(2),S06(1),S07(2),S09(5),S10(8),S11(1),S12A(3),S13(3),S14(5),S15(6),S16(11),S17(7),S18(4),S18A(2),A01(11),FB01(21),Gen.(41)	S01
B002	Tool	589	V01(1),V04(3),V05(3),S01(210),S02(67),S03(7),S05(1),S06(120),S07(129),S12(1),S12A(1),S16(3),S17(2),FB01(2),Gen.(39)	S01
B003	Gauge	28	V01(2),V02(3),S03(1),S05(1),S06(3),S07(3),S11(1),S14(7),S15(1),S16(1),Gen.(5)	S14
B004	Tool Holder	34	V05(1),S01(1),S02(6),S06(1),S16(3),S17(1),FB01(19),Gen.(3)	FB01
B005	Documents	2	Gen.(2)	NA
B006	Miscelleneous	1	S14(1)	S14

Table 8 The most vitiated stations of P1 facility by damaged machinery objects from 01.07.05 to 30.06.09

Code	Machinety Object	Total No. of Failures	Station(No. Failures)	Most Vitiated Station(s)
				Code
0001	Exhaust	7	GWM(1),V04(1),S01(2),S15(1),Gen.(1)	S01
0002	Gearbox	3	S07(1),S13(2)	S13
0003	Motor	32	GWM(8),V05(2),S01(1),S02(5),S03(2),S14(1),S15(6),S17(2),A01(2),FB01(1),Gen.(2)	GWM
0004	Headstock	0	NA	NA
0005	Tailstock	0	NA	NA
0006	Sliding Carriage	16	GWM(1),S01(5),S02(2),S03(1),S12A(1),S13(1),S14(2),S17(2),S18A(1)	S01
0007	Pump	42	GWM(1),V01(3),S01(3),S02(1),S10(3),S11(2),S14(4),S15(23),Gen.(2)	S15
0008	Fluorescent Lighting	14	V04(2),S01(3),S02(4),FB01(1),S12(4)	S12
0009	Switch Cabinet	23	GWM(1),V01(3),V02(3),V04(2),S03(1),S07(1),S11(1),S13(2),S14(4),S15(1),S17(2),FB01(2)	S14
0010	Hydraulic Cabinet	28	GWM(3),V01(11),V02(1),S03(2),S10(2),S14(7),S18A(2)	V01
0011	Protective Shield	53	GWM(2),V01(3),V02(1),V04(2),V05(2),S01(10),S02(5),S03(1),S06(1),S09(1),S12(1), S14(4),S16(3),S17(1),S18A(1),A01(5),Gen.(10)	S01
0012	Clamping	15	GWM(1),V04(1),S01(1),S02(3),S03(3),S13(1),S14(2),S15(1),S16(1),S18A(1)	S02,S03
0013	Conveyer Belt	51	GWM(1),S01(6),S02(2),S06(1),S12(1),S18A(1),A01(7),FB01(31),Gen.(1)	FB01
0014	Valve	72	GWM(1),V01(5),V02(2),S01(4),S01(1),S02(3),S03(7),S06(2),S09(1),S10(11),S13(3),S14(12),S16(12),S18(1),FB01(1),Gen.(6)	S14,S16
0015	Cylinder	77	V01(8),V02(2),V05(1),S01(12),S02(3),S03(6),S05(1),S07(2),S10(9),S11(3),S12A(1),S13(3),S14(8),S15(2),S16(2),S17(5),S18A(3),FB01(3),Gen.(4)	S01
0016	Cable/Wire	148	GWM(1),V01(6),V02(2),V04(1),V05(4),S01(14),S02(8),S03(7),S05(6),S06(26),S07(24),S09(1),S10(4),S12(3), S13(1),S14(15),S15(2),S16(8),S17(1),S18(4),S18A(2),A01(1),EDV1(1),Gen.(5)	S06
0017	Switch/Button	77	GWM(2),V01(9),V05(4),S01(10),S02(16),S03(1),S05(1),S06(3),S10(1),S11(2),S12(5),S12A(3),S14(3),S16(3),S17(2),S18(4),S18A(1),A01(2),FB01(1),Gen.(7)	S02
0018	End/Proximity Switch	32	GWM(2),V04(1),S01(6),S02(4),S03(4),S06(1),S09(1),S14(1),S13(1),S16(1),S17(4),S18(1),S18A(1),A01(4)	S01
0019	Display	43	V01(2),V02(2),V04(1),S01(8),S02(3),S03(1),S06(2),S07(4),S09(2),S10(3),S11(2),S12(1),S12A(1),S14(4),S15(3),S17(1),S18A(1),EDV1(1),Gen.(1)	S01
0020	Sensor Barrier	19	GWM(1),V01(5),V02(1),V04(3),S02(1),S03(6),S07(1),Gen.(1)	S03
0021	Key Switch	3	V01(1),V02(1),S01(1)	V01,V02,S01
0022	Documents	6	GWM(2),S18(1),EDV1(3)	EDV1
0023	Measuring Sensor	88	GWM(1),V01(7),V02(9),V04(1),V05(2),S02(1),S03(6),S05(4),S06(1),S07(1),S10(6),S11(2),S13(2),S14(30),S15(5),S16(1),S17(1),S18(1),Gen.(7)	S14
0024	Filter	28	GWM(1),S02(2),S11(2),S14(21),S18A(1),Gen.(1)	S14
0025	Heat Exchanger	2	S11(1),Gen.(1)	S11
0026	Gear Fastener	30	GWM(4),V04(2),S01(2),S03(1),S13(1),S14(1),S15(3),S17(3),A01(8),FB01(4),Gen.(1)	A01
0027	Switching/Control Element	115	GWM(8),V01(3),V02(2),V04(4),V05(5),S01(10),S02(5),S03(9),S05(2),S07(4),S09(3),S10(7),S11(2),S12A(1),S13(3),S14(5),S16(3),S17(5),S18(4),A01(10),EDV1(5),FB01(3),Gen.(12)	S01,A01
0028	Regulator	4	GWM(1),S09(1),S12A(1),S16(1)	GWM,S09,S12A,S16
0029	Ball Screw	0	NA	NA
0030	Hydraulic Pipe	3	S07(1),S14(2)	S14
0031	Linear Guider	1	S03(1)	S03
0032	Sleeve	0	NA	NA
0033	Turret	0	NA	NA
0034	Stored Program Control	9	V05(1),S05(1),S10(2),S14(1),S16(1),S17(1),EDV1(1),Gen.(1)	S10
0035	Measuring System	3	V02(1),S14(2),S15(1)	S14
0036	Dynamometer	0	NA	NA
0037	Miscelleneous	171	GWM(6),V01(4),V02(2),V04(3),S01(4),S01(48),S02(15),S03(5),S06(37),S07(19),S10(6),S11(2),S14(2),S15(2),S16(1),S18A(2),S18A(1),EDV1(1),FB01(8),Gen.(3)	S01

5.4 Problem Based Failure Analysis

As mentioned before, the problems in the SAP system at TRW-Schalke are divided into two groups of mechanical and electrical. Each problem group consists of a list of predefined problems which is used to identify nature of problems by operators or technicians. When a failure occurs, the operator or worker at the facility notifies the failure by choosing a problem type from the predefined list based on his judgment. When a confirmation is written by a technician after a repair, the mentioned lists are used again to report the problem nature. Figure 48 illustrates numerical variation of different electrical problems occurred in the P1 facility in four successive anni from 01.07.2005 to 30.06.2009, during which the total number electrical problems has been recorded as 503. In this period, no function, partial damage and control indicator failure have been the most frequently occurred and thus the most critical electrical problems among all listed with respective 314, 66 and 53 recorded occurrence. The classification of different electrical problems directly affects the quality of the undertaken statistical analysis and its output information. The more optimally detailed are the categories of the electrical problems, the higher is the value and usefulness of the output of the analysis.


Annual Synopsis of the Electrical Problems in P1 Facility

As the graph on the left shows, the most critical electrical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been 'no function', 'partial damage' and 'control indicator failure' for four successive anni. Nevertheless, the number of electrical problems which have been recorded as 'miscellaneous' shows a drastic rise in the last two anni from 01.01.2007 to 30.06.2009. This is not a favorable situation as this category does not indicate what actually the electrical problem was. There are some electrical problem categories which have been rarely used during the studied period. It is therefore essential to underline that the usefulness of the analysis outcomes can only be enhanced, if the problem classification is made optimally.

Figure 48 Number of electrical problems occurred in the P1 facility in annual cycles within the time period from 01.07.05 to 30.06.09.

There are two essential issues to be considered: The first is about the mechanical and electrical problem lists; better these lists are made, more understandable and useable they can be for the operators, and thus more effective in generating high quality information. For example, by looking at figure 48 it can be seen that some terms like no function and partial damage are relatively valueless for a technical analysis regarding the information they carry. It is apparent that when a failure occurs, most of the times there is no functionality and usually there exists a partial damage. These terms may help out explaining the situation, but as problem categories facilitate neither a technician nor an analyst with attaining any useful information. Therefore, it is vital to review, discuss and create new lists of problem categories in the system in a way to assist operators and workers with ease of use and to provide meaningful and valuable information for technicians and analyst.

The second issue is about the workers themselves; better they are technically trained at a basic level, higher is the probability that their problem assessment is correct. Their judgment is the factor based on which a job-fitted technician (i.e. an electrician, a mechanist or a repairman) is chosen to go and fix the problem. Obviously, a false assessment would bring only losses; therefore, adequate training and motivation is necessary for each and every of the workers and operators in plant. It needs to be underlined that the problem lists should as simple and as clear as possible for the operators with basic training and they have to be as comprehensive and as meaningful for the technicians. This is something in contradiction; there are only two ways to deal with such a challenge: either to have two separate sets of lists for operators and technicians or to have one set of an optimized list with some compromises to fit for use by both operators and technicians.

To illustrate the importance of these lists and their contents, just imagine the following case: an operator in a facility, because of either lack of knowledge or an inefficient problem list in hand, reports an electrical problem of light outfall as a miscellaneous mechanical problem. As the first consequence, a mechanist will go to the facility instead of an electrician since the main problem type is wrongly notified. The second consequence is that even when an electrician goes there afterwards, he may not have adequate or appropriate tools and spare parts with him to repair the problem as the problem category was not correctly mentioned. Then, he has to go back to his office or wait till somebody else brings what he needs. Added-up losses are: inefficient use of employees, waste of time, longer downtime, generation of false information and a dozen of other factors, each of which directly or indirectly can be counted as a negative flow of money. In any case, continuing with the undertaken object based failure analysis, figure 49 incorporates visualizes the significancy of different electrical problems. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total number of occurred electrical problems that is 503 between 01.07.2005 and 30.06.2009.

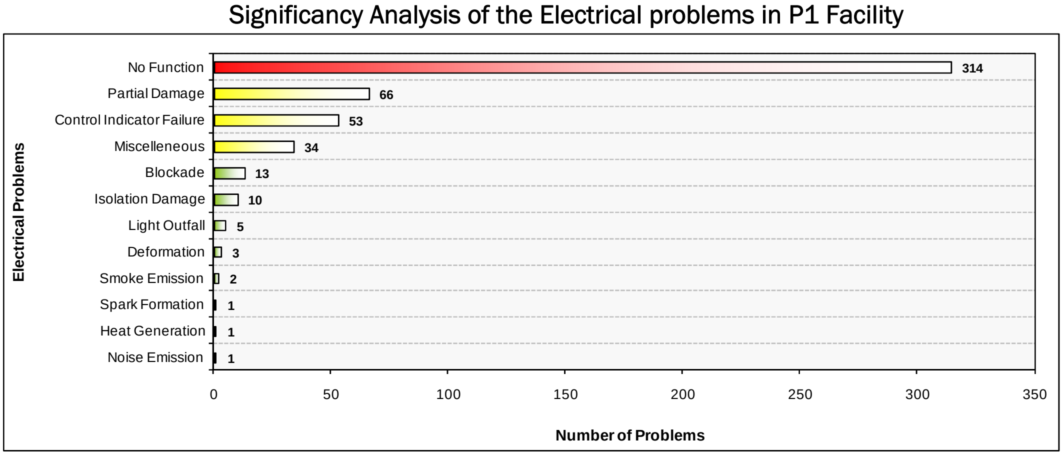
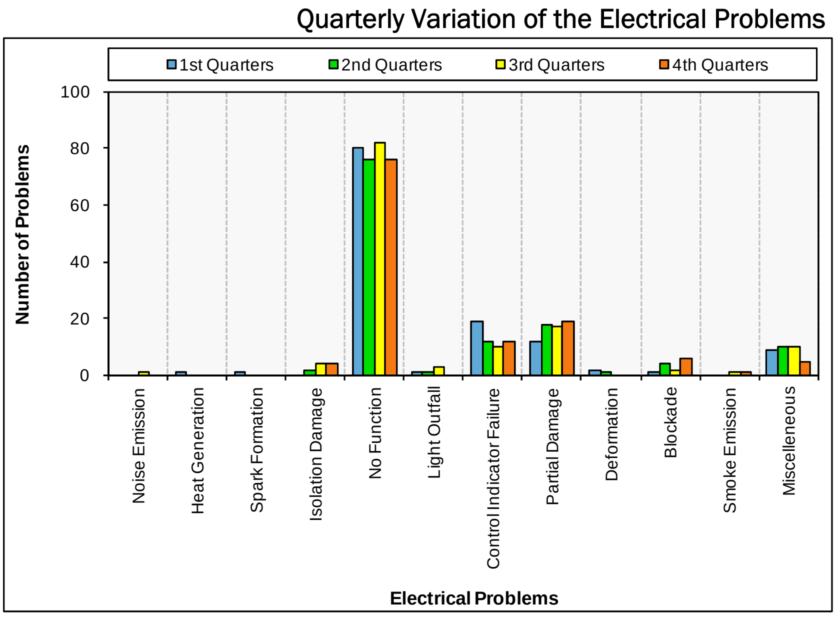


Figure 49 Number of different electrical problems occurred in the P1 facility between 01.07.05 and 30.06.09. There is an approximate multi-colored classification of 60%, 30% and 10% of the total number.

Based on the same methodology used to spot the plannedly maintainable stations, it is possible to identify which electrical problems are the most and least predictable problems. Using the relative standard deviation methodology, it is possible to identify the most and the least predictable electrical problem with the corresponding lowest and highest RSD. Derived from the monthly data from 01.07.2007 to 30.06.2009, in the P1 facility the most predictable problem is no function and the least predictable electrical problems are noise emission, heat generation and spark formation with respective 40% and 692.8% RSD. The word 'predictable' is used with a meaning associated with 'expected' rather than 'preventable'. The most predictable problem is not only the problem with the highest number of occurrence in a long period of time but also a problem which has shown similar periodic (e.g. monthly) behavior during the longer epoch (i.e. similar number of occurrence per month).

Moreover, the most and the least critical month of the year for the whole and each of the electrical problems can be determined as the months in which the electrical problems have had the largest and smallest number of occurrence respectively. For instance, for 'control indicator failure', the most critical month has been March with 3 occurrences on average. For the same electrical problem the least critical month has been July with almost no occurrence on average. Considering the whole electrical problems, the most and least critical months have been April and September, and December with respective 13 and 8 occurrences on average. On the quarterly basis, the electrical problems on the whole show similar criticality as the quarterly numbers of occurrence are very close to each other.

The variation of number of different electrical problems with respect to particular episodes of time is of great importance as well. Figure 50, in the next page, shows the variation of number of electrical problems with respect to the quarter in which they occurred. As shown for other entities like stations and machinery objects, depending on the situation and favored precision degree, the timely variation of number of electrical problems can be drawn on a monthly basis. Figure 51 represents such a monthly variation and can be employed to simply show the critical months for various electrical problems. As an example, the most critical month of a year for light outfall can be easily identified as August.



As the graph on the left presents, the most critical electrical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been ‘no function’, ‘partial damage’ and ‘control indicator failure’. While ‘no function’ has been a more incident problem in 3rd quarters ‘partial damage’ and ‘control indicator failure’ have been occurred more in 4th and 1st quarters respectively. Furthermore, while number of partial damages was the lowest in 1st quarters, for control indicator failures it was the case in 3rd quarters. An essential issue is the terms used to categorize the electrical problems: e.g. while ‘control indicator failure’ denotes perfectly a problem, ‘no function’ signifies the situation rather than specifying the problem itself.

Figure 50 Number of electrical problems in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

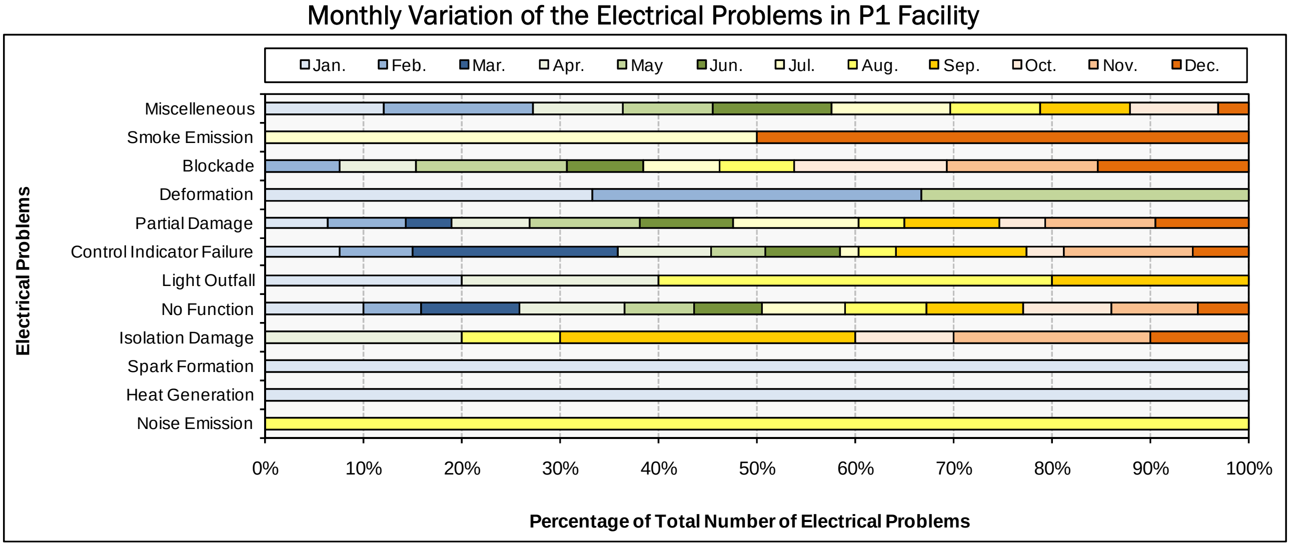
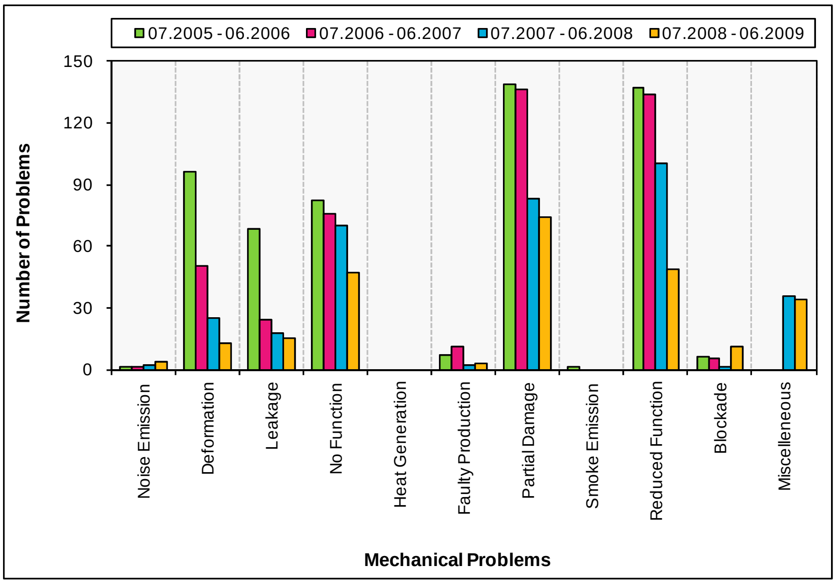


Figure 51 A chart representing the percentage of electrical problems in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09.

Coming to the analysis of mechanical problems, figure 52, in the next page, illustrates the change of number of different mechanical problems occurred in the P1 facility in four successive anni from 01.07.2005 to 30.06.2009, during which the total number mechanical problems has been recorder as 1561. In this period of time, partial damage, reduced function and no function have been the most frequently occurred and thus the most critical mechanical problems among all the listed categories with respective 432, 420 and 275 recorded occurrences.

Similar to the previous cases, the classification of different mechanical problems directly affects the quality of the undertaken statistical analysis and its output information. The more optimally detailed are the categories of the mechanical problems, the higher are the value and usefulness of the outputs of the analysis. The mechanical problems list in hand does not sound to be optimally created. As before, there are a few very general terms as problem categories (e.g. partial damage or reduced function), use of which does not facilitate extracting very helpful information.

Annual Synopsis of the Mechanical Problems in P1 Facility



As the graph on the left shows, the most critical mechanical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been 'partial damage', 'reduced function' and 'no function' for four successive anni. Moreover, the number of mechanical problems on the whole indicates a steady decrease during the studied period except for 'blockade' and 'noise emission' which have a slight increase in the last annum. Besides, the number of mechanical problems recorded as 'miscellaneous' shows a drastic rise in the last two anni from 01.01.2007 to 30.06.2009. This is not a favorable situation as this category does not directly express what actually the mechanical problems were. It is essential to optimize the problem list.

Figure 52 Number of mechanical problems occurred in the P1 facility in annual cycles within the time period from 01.07.05 to 30.06.09

Figure 53 presents the significancy of different predefined mechanical problems that have been occurred in the P1 facility from 01.07.2005 to 30.06.2009. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total number of occurred mechanical problems that is 1561 in the mentioned period. For example, approximately 60% of the total number of mechanical problems has been recorded as partial damage, reduced function and no function, while roughly 30% as deformations and leakages and only less than 10% as blockade, faulty production, noise and smoke emission, and miscellaneous.

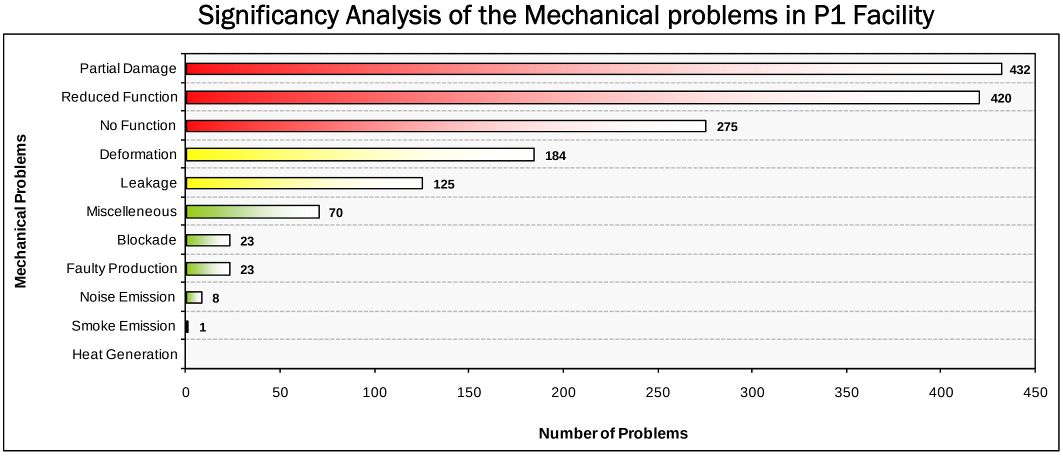
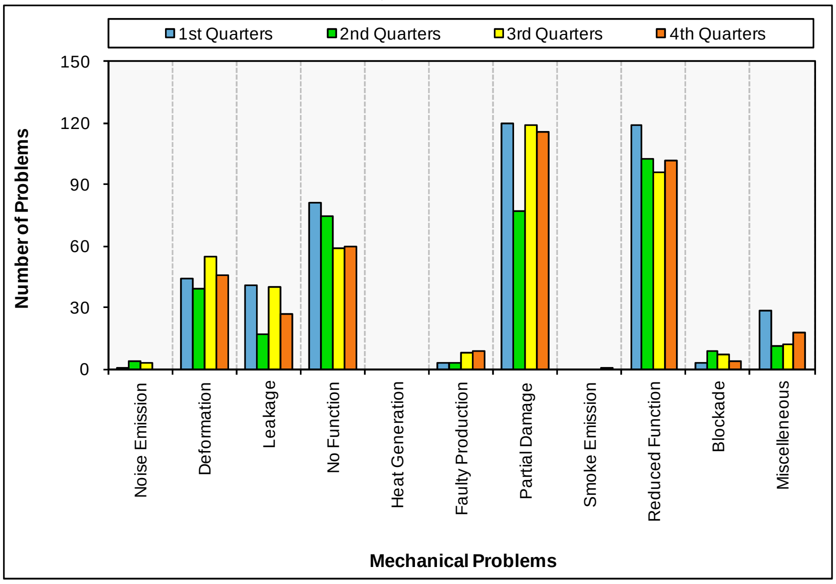


Figure 53 Number of different mechanical problems occurred in the P1 facility between 01.07.05 and 30.06.09; there is an approximate multi-colored classification of 60%, 30% and 10% of the total number.

Like before, it is possible to identify which mechanical problems are the most and least predictable problems. Using the relative standard deviation methodology, it is possible to identify the most and the least predictable mechanical problem with the respective lowest and highest RSD. Based on the monthly data from 01.07.2007 to 30.06.2009, in the P1 facility the most predictable mechanical problem is no function and the least predictable mechanical problem is smoke emission with respective 48.3% and 692.8% RSD. Additionally, the most and the least critical month of the year for the whole and each of the mechanical problems can be identified as the months in which the mechanical problems have had the largest and smallest number of occurrence respectively. To illustrate, for 'deformation', the most critical month has been September with 8 occurrences on average. For the same problem the least critical months has been April and December with 2 occurrences on average. Considering all the problems, the most and least critical months are September and May, and December with respective 48 and 25 occurrences on average.

The numerical variation of different mechanical problems with respect to particular epochs of time is of great importance as well. Figure 54 presents the numerical variation of mechanical problems with respect to the quarter in which they occurred. As shown for other entities like stations and machinery objects, depending on the situation and favored precision degree, the timely variation of number of mechanical problems can be drawn on a monthly basis. Figure 55 represents such a monthly variation and can be employed to simply show the critical months for various mechanical problems. For instance, the most critical month of a year for faulty production can be easily determined as November.

Quarterly Variation of the Mechanical Problems in P1 Facility



As the graph on the left presents, the most critical mechanical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been ‘partial damage’, ‘reduced function’ and ‘no function’. While ‘partial damage’ has been a more incident problem in 1st and 3rd quarters, ‘reduced function’ and ‘no function’ have been occurred more in 1st quarters only. Furthermore, while number of partial damages was the lowest in 2nd quarters, for problem of reduced function it was the case in 3rd quarters. As for electrical problems, an essential issue is the terms used to categorize the mechanical problems: e.g. while ‘leakage’ denotes perfectly a problem, ‘no function’ or ‘reduced function’ signifies the situation rather than specifying the problem itself.

Figure 54 Number of mechanical problems in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

Monthly Variation of the Mechanical Problems in P1 Facility

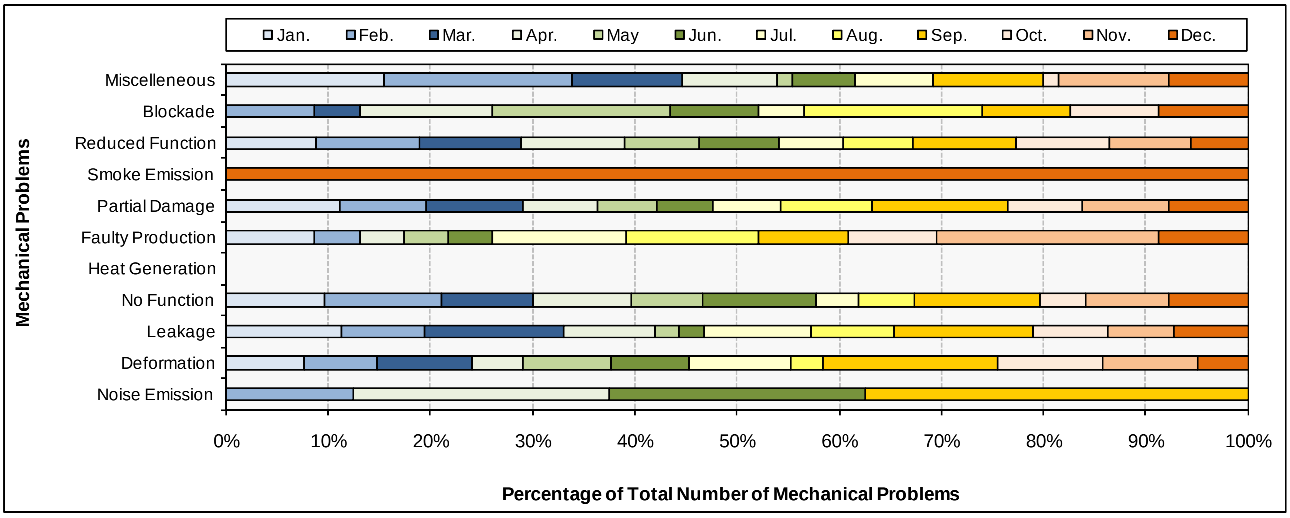


Figure 55 Percentage of mechanical problems in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

In general, undertaking a problem based failure analysis is very useful in determining the most appropriate nondestructive tests and condition monitoring techniques for a facility or a plant in general. Knowing that which electrical or mechanical problems occurs the most and in which facility or station helps employing facility-specific maintenance tactics and technologies. Utilizing proper maintenance tactics, technologies, techniques and tests, gradually trim down the number of occurred problems and rise the availability and productivity of the facility. With this clarification the importance of having optimally made problem lists is underlined again. Better these lists are made, higher quality outputs come out of the analysis, more appropriate tactics and technologies are employed, and less number of problems will occur in the future.

Note that knowing specific mechanical or electrical problems in a facility or plant, the maintenance department and more specifically the technicians can be equipped with adequate tools to identify potential failures in advance and prevent them before happening. For example, if there has been a problem of leakage in a specific station of a facility, proper tools can be utilize to inspect that specific station and its machinery for a particular problem of leakage on a regular basis; this way it is highly probable to identify potential leakages before occurrence and to prevent a minor or major failure, hence, saving money. In other words, with such information in hand one can optimally define and schedule planned maintenance activities for each specific station getting use of all available resources to achieve the best results. For this reason, tables 9 and 10 are structured in a way to indicate the most problematic station based on particular predefined problems. To illustrate, considering the information provided in the below tables, it is known that station S14 is the most problematic station regarding the leakage problem or control indicator failure. Having this information in hand a maintenance planner can schedule routine inspections in station S14 for the mentioned problems. Moreover, a maintenance analyst may identify the best tools and methods to discover leakages. As a result, a mechanist can go and inspect the station for leakages with proper equipment and sufficient knowledge about the potential problem he has to look for. This is the same for an electrician who goes to inspect control indicators on a planned schedule. Although this information is vital, but it is possible to go a step forward and to identify which type of problems are more associated with which type of machinery objects. In other words, it is possible to identify the most problematic machinery part based on a specific predefined problem. This helps the maintenance department to know exactly the problems related to specific objects and utilize all of its resources to prevent them.

Table 9 The most problematic P1 stations based on occurred electrical problems between 01.07.05 and 30.06.09

Code	Electrical Problem	Total No. of Occurrence	Station(No. of Occurrence)	Most Problematic Station(s)
CE01	Noise Emission	1	S11(1)	S11
CE02	Heat Generation	1	S13(1)	S13
CE03	Spark Formation	1	S02(1)	S02
CE04	Isolation Damage	10	GWM(1),V01(2),V05(1),S02(3),S18(1),Gen.(2)	S02
CE05	No Function	314	GWM(9),V01(11),V02(10),V04(9),V05(4),S01(21),S02(27),S03(26),S05(7),S06(27),S07(24),S09(2),S10(21),S11(2),S12(7),S12A(2),S13(9),S14(19),S15(12),S16(4),S17(14),S18(8),S18A(2), A01(12),EDV1(6),FB01(4),Gen.(15)	S02,S06
CE06	Light Outfall	5	V01(2),S01(1),S02(1),S12(1)	V01
CE07	Control Indicator Failure	53	GWM(1),V01(3),V02(3),S01(3),S02(1),S03(2),S05(1),S07(2),S10(1),S11(4),S12(1),S14(18),S15(1),S17(3),A01(4),FB01(1),Gen.(2)	S14
CE08	Partial Damage	66	GWM(1),V01(6),V02(3),V04(2),V05(1),S01(7),S02(2),S03(6),S05(2),S06(3),S07(11),S10(2),S11(1),S12(3),S12A(2),S14(2),S15(1),S16(5),S18(2),S18A(1),Gen.(4)	S07
CE09	Deformation	3	S02(1),Gen.(2)	S02
CE10	Blockade	13	GWM(3),V02(1),S03(1),S14(3),S15(2),S17(1), A01(1),Gen.(1)	GWM,S14
CE11	Smoke Emission	2	V05(1),S10(1)	V05
CE12	Miscelleneous	34	GWM(2),V01(3),V02(3),V04(2),V05(1),S01(3),S02(1),S03(3),S05(2),S10(4),S11(2),S14(3),EDV1(3),FB01(1),Gen.(1)	S10

Table 10 The most problematic P1 stations based on occurred mechanical problems between 01.07.05 and 30.06.09

Code	Mechanical Problem	Total No. of Occurrence	Station(No. of Occurrence)	Most Problematic Station(s)
3001	Noise Emission	8	GWM(2),V05(1),S03(1),S14(1),S15(1),FB01(2)	GWM,FB01
3002	Deformation	184	V04(2),V05(1),S01(133),S02(27),S03(1),S14(1),S16(1),S18A(1),FB01(2),Gen.(13)	S01
C003	Leakage	125	GWM(2),V01(16),V02(1),S01(8),S02(2),S03(6),S09(1),S10(13),S11(2),S12A(1),S13(3),S14(32),S15(3),S16(13),S18A(1),A01(7),Gen.(13)	S14
C004	No Function	275	GWM(9),V01(3),V02(1),V04(1),V05(3),S01(15),S02(5),S05(2),S06(80),S07(78),S09(2),S10(3),S13(1),S14(14),S15(14),S16(4),S17(4),S18(4),S18A(1),A01(4),EDV1(1),FB01(4),Gen.(20)	S06
C005	Heat Generation	0	NA	NA
C006	Faulty Production	23	V01(3),V02(1),V04(1),V05(1),S01(3),S02(2),S03(2),S05(2),S06(3),S09(2),FB01(1),Gen.(1)	V01,S01,S06
C007	Partial Damage	432	GWM(5),V01(9),V02(2),V04(9),V05(6),S01(141),S02(54),S03(11),S06(31),S07(29),S09(4),S10(1),S11(3),S12A(1),S13(2),S14(3),S15(5),S16(9),S17(9),S18(2),S18A(2),A01(8),FB01(40),Gen.(46)	S01
C008	Smoke Emission	1	GWM(1)	GWM
C009	Reduced Function	420	GWM(12),V01(14),V02(6),V04(3),V05(2),S01(37),S02(34),S03(17),S05(2),S06(43),S07(40),S09(4),S10(13),S11(5),S12(3),S12A(4),S13(5),S14(44),S15(18),S16(16),S17(9),S18(5),S18A(7),A01(12),EDV1(2),FB01(33),Gen.(30)	S14
C010	Blockade	23	GWM(4),V04(1),S01(3),S02(1),S06(5),S07(4),S12A(1),S14(1),A01(2),FB01(1)	S06
C011	Miscelleneous	70	V01(1),V02(2),V04(4),V05(5),S01(9),S02(7),S03(1),S06(5),S07(2),S10(3),S12(1),S12A(1),S13(2),S14(3),S16(3),S18A(4),FB01(8),Gen.(9)	S01

Tables 11 and 12 show the most problematic machinery objects based on predefined electrical and mechanical problems. For example, it can be easily seen that valves are most frequently coupled with leakage problem or protective shields with deformation. It is indispensable to note that better the lists of electrical and mechanical problems and also the machinery objects are made, better and more reliable is the resultant information out of the undertaken analyses. Knowing the most frequent problem of a machinery object or the most frequent problem occurring in a station of facility is priceless information that can be obtained from problem based failure analysis. Such information can be used widely by maintenance department to get use of the most appropriate condition monitoring techniques and nondestructive test for a particular facility or machinery object and also to prepare and schedule planned maintenance activities in the most effective way. Therefore, here comes the same predicament again, if the problem lists were designed in a more comprehensible and practical way and if the workers were more aware how precious is the information they provide and acted accordingly with higher sense of responsibility, then the reliability of this information was so high that facilitated the stakeholders with the aptitude to make correct decisions and to move towards perfectly-fitted solutions. Now that the importance of making up perfectly structured problem lists and awareness of the workers and operators in a facility are evidently imaged for the stakeholders, it is expected to attain more reliable information with higher quality in the coming future.

Table 11 The most problematic machinery objects based on occurred electrical problems between 01.07.05 and 30.06.09

Code	**Electrical Problem**	**Total No. of Occurrence**	**Machinery Object(No. of Occurrence)**	**Most Problematic Object**	
CE01	Noise Emission	1	0025(**1**)	**0025**	Heat Exchanger
CE02	Heat Generation	1	0027(**1**)	**0027**	Sw itching/Control Element
CE03	Spark Formation	1	0017(**1**)	**0017**	Sw itch/Button
CE04	Isolation Damage	10	0016(**8**),0023(**1**),0027(**1**)	**0016**	Cable/Wire
CE05	No Function	285	0001(**2**),0002(**2**),0003(**12**),0006(**1**),0007(**1**),0008(**7**),0009(**14**),0010(**2**),0011(**2**),0012(**3**),0013(**2**),0014(**2**),0015(**4**),0016(**65**),0017(**29**),0018(**11**),0019(**20**),0020(**12**),0021(**2**),0022(**4**),0023(**25**),0026(**2**),0027(**45**),0028(**1**),0034(**7**),0035(**1**),0037(**7**)	**0016**	Cable/Wire
CE06	Light Outfall	5	0008(**3**),0017(**2**)	**0008**	Fluorescent Lighting
CE07	Control Indicator Failure	53	0009(**5**),0016(**3**),0018(**6**),0019(**10**),0020(**1**),0023(**20**),0026(**1**),0027(**6**),0035(**1**)	**0023**	Measuring Sensor
CE08	Partial Damage	60	0003(**1**),0009(**2**),0011(**2**),0016(**29**),0017(**12**),0018(**3**),0019(**1**),0020(**2**),0023(**3**),0027(**5**)	**0016**	Cable/Wire
CE09	Deformation	3	0017(**2**),0023(**1**)	**0017**	Sw itch/Button
CE10	Blockade	13	0003(**2**),0014(**1**),0016(**1**),0017(**1**),0023(**2**),0026(**2**),0027(**3**),0037(**1**)	**0027**	Sw itching/Control Element
CE11	Smoke Emission	2	0016(**1**),0037(**1**)	**0016**	Cable/Wire
CE12	Miscelleneous	34	0008(**1**),0009(**1**),0016(**2**),0017(**1**),0018(**1**),0019(**1**),0020(**1**),0021(**1**),0022(**1**),0023(**7**),0026(**1**),0027(**4**),0034(**2**),0037(**10**)	**0023**	Measuring Sensor

Table 12 The most problematic machinery objects based on occurred mechanical problems between 01.07.05 and 30.06.09

Code	**Mechanical Problem**	**Total No. of Occurrence**	**Machinery Object(No. of Occurrence)**	**Most Problematic Object(s)**	
3001	Noise Emission	8	0001(**1**),0003(**5**),0010(**1**),0013(**1**)	**0003**	Motor
3002	Deformation	17	0011(**2**),0013(**1**),0017(**2**),0030(**1**),0037(**11**)	**0011,0017**	Protective Shield,Sw itch/Button
C003	Leakage	112	0001(**1**),0007(**12**),0010(**15**),0011(**3**),0012(**3**),0014(**33**),0015(**22**),0016(**16**),0025(**1**),0026(**1**),0027(**1**),0028(**2**),0030(**1**),0037(**1**)	**0014**	Valve
C004	No Function	112	0001(**1**),0002(**1**),0003(**3**),0006(**2**),0007(**12**),0008(**1**),0010(**3**),0011(**4**),0012(**1**),0013(**4**),0014(**5**),0015(**11**),0016(**10**),0017(**1**),0018(**4**),0022(**1**),0023(**4**),0024(**7**),0026(**2**),0027(**12**),0030(**1**),0037(**22**)	**0007,0027**	Pump,Sw itching/Control Element
C005	Heat Generation	0	NA	NA	NA
C006	Faulty Production	7	0014(**2**),0023(**2**),0037(**3**)	**0014,0023**	Valve,Measuring Sensor
C007	Partial Damage	172	0001(**1**),0003(**1**),0006(**4**),0009(**1**),0011(**22**),0012(**3**),0013(**24**),0014(**6**),0015(**6**),0016(**5**),0017(**10**),0018(**4**),0019(**2**),0020(**3**),0023(**2**),0024(**2**),0026(**7**),0027(**9**),0031(**1**),0037(**59**)	**0013**	Conveyer Belt
C008	Smoke Emission	1	0026(**1**)	**0026**	Gear Fastener
C009	Reduced Function	246	0001(**1**),0003(**4**),0006(**8**),0007(**15**),0008(**1**),0010(**9**),0011(**11**),0012(**5**),0013(**14**),0014(**20**),0015(**32**),0016(**7**),0017(**14**),0018(**3**),0019(**9**),0023(**20**),0024(**19**),0026(**7**),0027(**26**),0028(**1**),0035(**2**),0037(**18**)	**0027**	Sw itching/Control Element
C010	Blockade	19	0003(**4**),0013(**1**),0014(**1**),0017(**1**),0026(**5**),0026(**1**),0027(**1**),0037(**5**)	**0026**	Gear Fastener
C011	Miscelleneous	54	0006(**1**),0007(**1**),0008(**1**),0011(**6**),0013(**4**),0014(**2**),0015(**2**),0016(**1**),0017(**1**),0023(**1**),0027(**2**),0037(**32**)	**0011**	Protective Shield

5.5 Cause Based Failure Analysis

The next step towards completing a statistical failure analysis is to undertake cause based failure analyses. This is basically to identify what the most frequent and predictable problem-causes are, and to determine which stations and machinery objects are more degraded by particular problem-causes. Knowing causes of problems helps discovering root causes which founded these problems. Therefore, having extensive information about the causes of the problems in a facility or for a machinery object is one of the most important steps towards effectively preventing the problems or failures.

In the SAP system of the TRW Schalke, like the case of problems, there are two lists of problem-causes, an electrical and a mechanical one. Each list consists of different causes and their related codes. After fixing a problem in the plant, these lists should be used by the technicians to state the cause or causes of the particular problem. It sounds logical that the list of electrical problems causes is usually but not always used by electricians and the mechanical one by mechanists and both lists by repairmen. However, the list of electrical problem causes has never been used by any technician. Of course, there can be problems whose nature is wrongly recorded by workmen at the facility, but it is impossible to have 503 electrical problems in a period of 48 months whose causes are all mechanical.

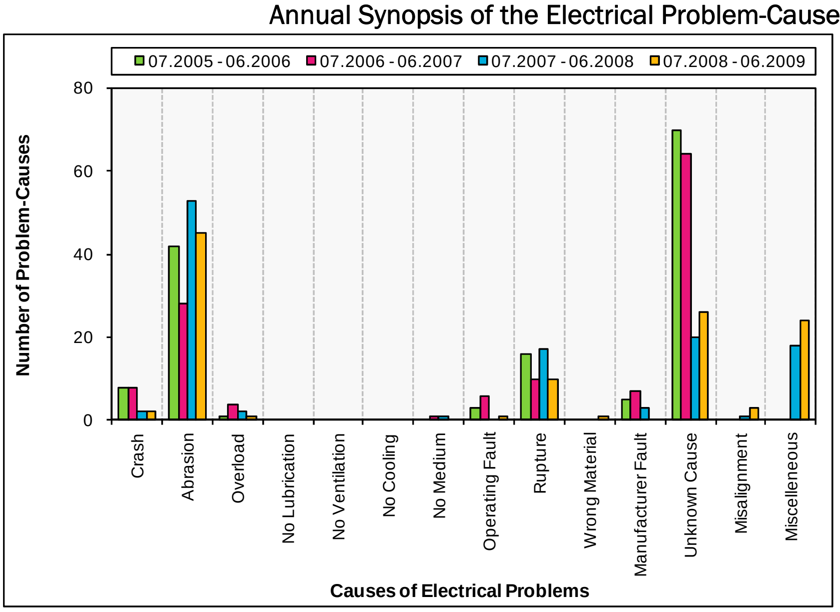
Identifying the reasons behind such problems in any plant is not as simple as it seems. On the face of it, technicians and more specifically electricians are to be blamed. They simply chose an option from the list of mechanical causes, and did not bother themselves to look at the other list and spend a few seconds more. But certainly, it was a task for departments in charge in TRW-Schalke to train them in a way to do their duties in a more responsible manner. One may ask why it is so important to provide such information; the reply relies on how it enlightens the path to make the right decisions. For example, think of a case in which many problems are recorded as electrical ones which are later found to be mechanical with related mechanical causes. This provides the management with a conclusion: the workmen at the facility need more training since they are incapable of simply making correct assessment which wastes time and money.

There are some other benefits involved in providing reliable information. To illustrate, when a problem cause is recorded by technicians with an abnormal frequency of occurrence or quantity, it will become a precedence to undertake a root cause analysis and to use all necessary resources in order to avoid or prevent the cause, and thus many related problems in the facility. Moreover, it is vital to make such a list complete but practical enough and to train the technicians adequately effective so as not to coerce them using such a category like an ‘unknown cause’ quite often. For further developments again there are only two alternatives: either to have two separate sets of lists for operators and technicians or to have one set of optimal lists with some compromises to be suitable for use by both groups.

Indeed, it is not expected from workmen and operators in all industrial plants to be able to identify causes of problems. This is rather the duty of technicians who fix the notified problems and write completion confirmations including feedbacks. It is understandable that even they may not be able to exactly identify cause(s) of a problem. This is exactly the challenge behind designing optimal lists of mechanical and electrical problem-causes which can be easily and effectively used by technicians. Despite of the mentioned problem and for the sake of a meaningful analysis, the author has divided the used list of problem-causes into two electrical and mechanical lists each linked to the corresponding problems. In other words, it has been assumed to classify the causes of electrical problems as electrical problem-causes and the causes of mechanical problems as mechanical problem-causes. This way it is possible to identify which causes have been the grounds for which type of problems.

Now that the classification process has been explained, the focus can be moved on the cause based failure analysis. Figure 56, in the next page, illustrates the change of number of different electrical problem-causes incurred in the P1 facility in four successive anni from 01.07.2005 to 30.06.2009. In this period of time, unknown cause, abrasion and rupture have been the most frequently incurred and thus the most critical electrical problem-causes among all the listed categories with respective 180, 168 and 53 recorded incurrence. Like the preceding cases, the classification of different electrical problem-causes directly affects the quality of the undertaken statistical analysis and its output information. The more optimally detailed are the categories of the electrical problem-causes, the higher is the value and usefulness of the output of the analysis.

The current list of the electrical problem-causes should be reviewed by maintenance experts for possible optimizing modifications. In addition to the classification of causes itself, the use of particular categories is of concern. Having 180 unknown causes for 503 electrical problems in four anni represents 35.8% of total number of cases: the causes of more than one third of electrical problems occurred during the studied period have been reported as and indeed are unknown.



As the graph on the left shows, excluding the unknown and miscellaneous causes, the most critical electrical problem-causes incurred in the P1 facility from 01.07.2005 to 30.06.2009 have been 'abrasion', 'rupture' and 'crash' for four successive anni. Nevertheless, the number of electrical problem-causes which have been recorded as 'unknown' shows an acceptable decrease while the ones recorded as 'miscellaneous' shows a drastic rise in the last two anni from 01.01.2007 to 30.06.2009. There are electrical problem-causes categories which have been never used during the studied period such as 'no lubrication' or 'no ventilation'. Therefore, it is essential to review and modify the cause list according to the needs.

Figure 56 Number of electrical problem-causes incurred in the P1 facility in annual cycles within the time period from 01.07.05 to 30.06.09

Figure 57 shows the significancy of different predefined electrical problem-causes that have been linked to the occurred electrical problems in the P1 facility from 01.07.2005 to 30.06.2009. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total number of incurred electrical problem-causes that is 503 in the mentioned period. Approximately 60% of the total number of causes has been recorded as either unknown or abrasion, while roughly 30% as rupture, miscellaneous and crash and only less than 10% as manufacturer fault, operating fault, overload, misalignment, no medium and wrong material.

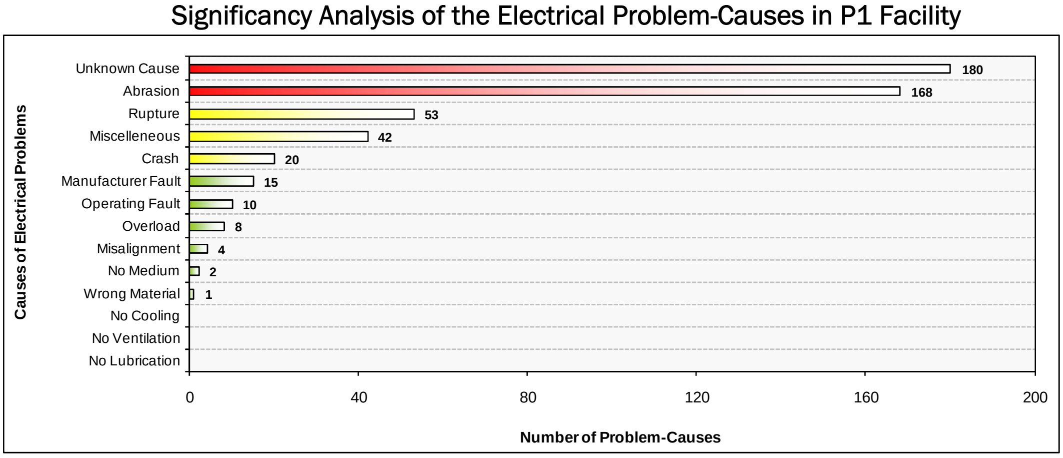
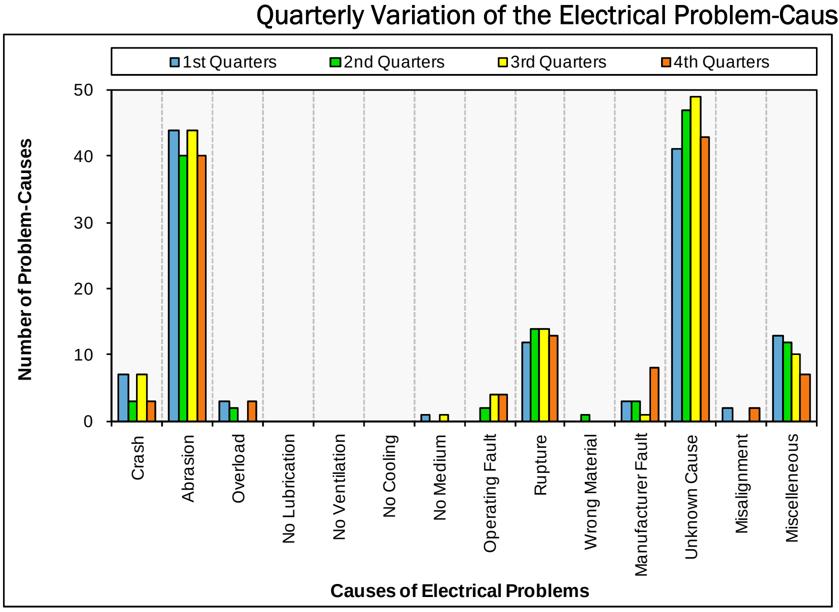


Figure 57 Number of different electrical problem-causes incurred in the P1 facility between 01.07.05 and 30.06.09.; there is an approximate multi-colored classification of 60%, 30% and 10% of the total number.

As it has been mentioned above, excluding unknown causes, most of the electrical problems in P1 facility have been caused abrasion. Having this information, most appropriate condition monitoring techniques and nondestructive tests plus other condition based maintenance tools can be used to identify or even predict formation abrasion. Or, for example in the case of operating faults, the root causes of these human faults can be investigated or even the operators or workmen in the plant can be accordingly trained.

It is also possible to determine the most and least predictable problem-causes. The most predictable electrical problem-cause is the one associated with the lowest RSD and the least predictable one is linked to the highest RSD value. Based on the monthly data from 01.07.2007 to 30.06.2009, in the P1 facility the most predictable electrical problem-cause is abrasion and the least predictable electrical problem-cause is wrong material with 39.7% and 400% RSD correspondingly. Moreover, the most and the least critical months of the year for the whole and each of the electrical problem-causes can be identified as the months in which the electrical causes have had the largest and smallest number of incurrence respectively. To illustrate, for ‘abrasion’, the most critical month has been September with 6 incurrence on average. For ‘abrasion’, the least critical months have been April and December with 2 incurrence on average. Considering all the electrical problem-causes, the most and least critical months are April and September, and December with respective 4 and 2 incurrence on average.

The variation of number of different electrical problem-causes with respect to particular periods of time carries considerable important information. Figure 58 presents the numerical variation of electrical problem-causes with respect to the quarter in which they incurred. As shown for other entities like stations and machinery objects, depending on the situation and favored precision degree, the timely variation of number of mechanical problems can be drawn on a monthly basis. Figure 59 represents such a variation monthly, and can be employed to simply show the critical months for various mechanical problems. For instance, the most critical month of a year for rupture seems to be February.



As the graph on the left shows, the most critical electrical problem-causes known and occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been ‘abrasion’, ‘rupture’ and ‘crash’. ‘Abrasion’ has been a more incident problem-cause in 2nd and 4th quarters. ‘Rupture’ and ‘crash’ have been incurred more in 2nd and 3rd quarters, and 1st and 3rd quarters respectively. Furthermore, while number of abrasions was the lowest in 2nd and 4th quarters, for ruptures it was the case in 1st quarters. An essential issue is the terms used to categorize the electrical problem-causes: e.g. while ‘abrasion’ or ‘overload’ denote perfectly a problem-cause, ‘crash’ signifies the situation rather than specifying the problem-cause itself.

Figure 58 Number of electrical problem-causes in the P1 facility with respect to the quarter of incurrence from 01.07.05 to 30.06.09

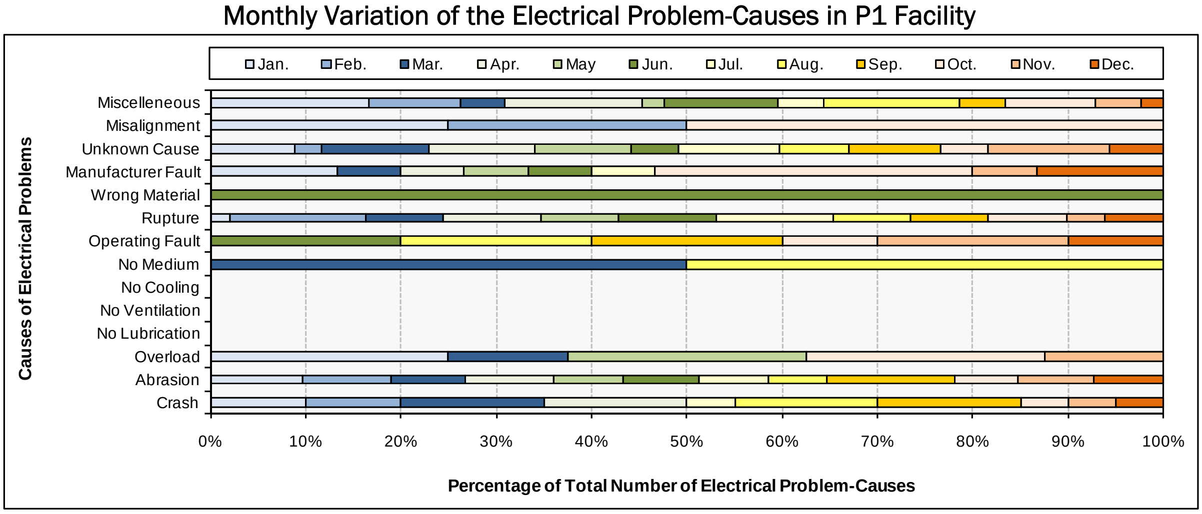
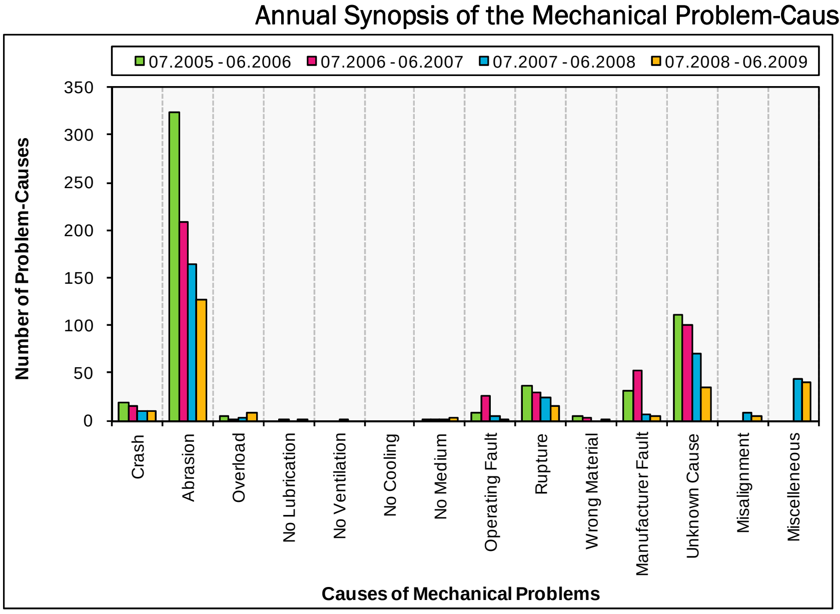


Figure 59 Percentage of electrical problem-causes in the P1 facility with respect to the month of incurrence from 01.07.05 to 30.06.09

Analyzing mechanical problem-causes, figure 60 presents the change of number of different mechanical problem-causes incurred in the P1 facility in four successive anni from 01.07.2005 to 30.06.2009. In this period, abrasion, unknown cause and rupture have been the most frequently incurred and thus the most critical mechanical problem-causes among all the listed categories with respective 822, 317 and 107 recorded incurrence. Similar to the preceding cases, the classification of different mechanical problem-causes directly affects the quality of the undertaken SFA and its output information. The more optimally detailed are the categories of the mechanical problem-causes, the higher is the value and usefulness of the output of the analysis. The current list of mechanical problem-causes should be reviewed by maintenance experts for possible optimizing modifications. Having 317 unknown causes for 1561 mechanical problems in four anni represents 30.3% of total number of cases: the causes of more than one third of mechanical problems occurred during the studied period have been reported as and indeed are unknown, as it was the case of electrical problem-causes.



As the graph on the left shows, excluding the unknown causes, the most critical mechanical problem-causes incurred in the P1 facility from 01.07.2005 to 30.06.2009 have been ‘abrasion’, ‘rupture’ and ‘manufacturer fault’ for four successive anni. Nevertheless, the total number of mechanical problem-causes which have been recorded as ‘unknown’ shows an acceptable decrease while the ones recorded as ‘miscellaneous’ shows a relatively drastic rise in the last two anni from 01.01.2007 to 30.06.2009. The mechanical problem-cause ‘no cooling’ has been never used during the studied period. Indeed, it is essential to review and modify the mechanical problem-causes list according to the needs and based on the professional information.

Figure 60 Number of mechanical problem-causes incurred in the P1 facility in annual cycles within the time period from 01.07.05 to 30.06.09

Figure 61 shows the significancy of different predefined mechanical problem-causes that have been linked to the occurred mechanical problems in the P1 facility from 01.07.2005 to 30.06.2009. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total number of incurred mechanical problem-causes that is 1561 in the mentioned period. Approximately 60% of the total number of causes has been recorded as either abrasion or unknown, while roughly 30% as rupture, manufacturer fault and miscellaneous, and only less than 10% as the other categories.

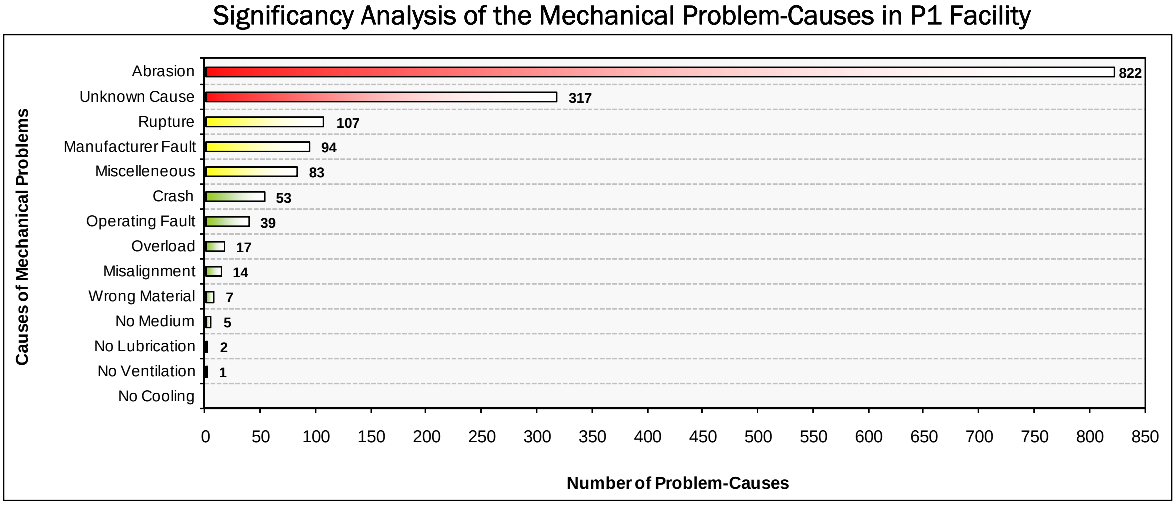
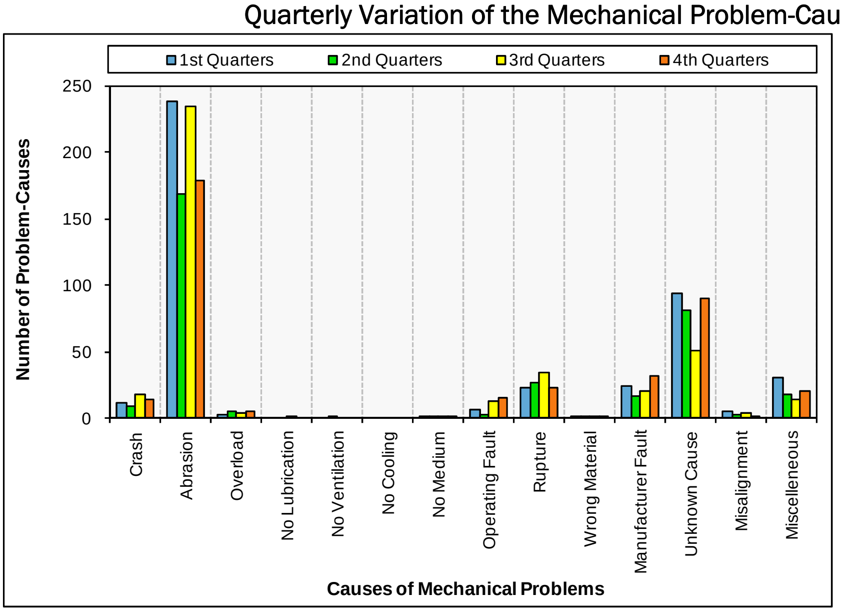


Figure 61 Total occurrence number of different mechanical problem-causes in the P1 facility from 01.07.05 to 30.06.08. There is an approximate multi-colored classification of 60%, 30% and 10% of the total number.

The most and the least critical months of the year for the whole and each of the mechanical problem-causes are known as the months in which the mechanical causes have had the largest and smallest number of incurrence respectively. To illustrate, for 'abrasion', the most critical month has been September with 28 incurrence on average. For the same problem-cause the least critical month has December with 11 incurrence on average. Considering all the mechanical problem-causes, the most and least critical months are September and May with respective 12 and 6 incurrence on average. Note that the critical months for mechanical problem-causes are logically as same as the critical months for mechanical problems.

The numerical variation of different mechanical problem-causes with respect to particular periods of time carries considerable important information. Figure 62 illustrates the numerical variation of mechanical problem-causes with respect to the quarter in which they incurred. As shown for other entities like stations and machinery objects, depending on the situation and favored precision degree, the timely variation of number of mechanical problems can be drawn on a monthly basis. Figure 63 represents such a variation monthly and can be employed to simply show the critical months for various mechanical problems. For example, the most critical month of a year for misalignment is August.



As the graph on the left shows, the most critical mechanical problem-causes known and occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been 'abrasion', 'rupture' and 'manufacturer fault'. Abrasion has been a more incident problem-cause in 1st quarters. Rupture and manufacturer fault have been incurred more in 3rd and 4th quarters respectively. Furthermore, while number of abrasions was the lowest in 2nd quarters; for ruptures and manufacturer faults it was the case in 3rd and 2nd quarters respectively. An essential issue is the terms used to categorize the mechanical problem-causes: e.g. while 'misalignment' denotes perfectly a problem-cause, 'crash' signifies the situation rather than specifying the problem-cause itself.

Figure 62 Number of mechanical problem-causes in the P1 facility with respect to the quarter of incurrence from 01.07.05 to 30.06.09

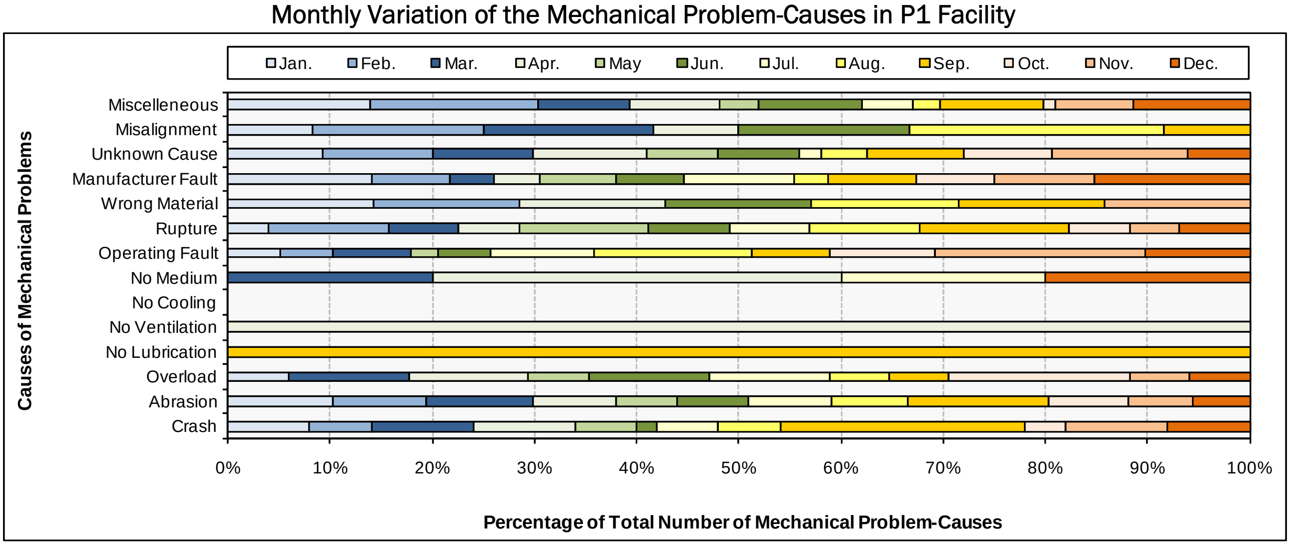


Figure 63 Percentage of mechanical problem-causes in the P1 facility with respect to the month of incurrence from 01.07.05 to 30.06.09

Undertaking a caused based failure analysis is very helpful to identify the most appropriate nondestructive tests and condition monitoring techniques for a facility or a plant. Knowing that which electrical or mechanical problem-causes incur the most and in which facility or station helps employing facility-specific maintenance tactics and technologies. Utilizing proper maintenance tactics, technologies, techniques and tests, gradually trim down the number of incurred problem-causes and thus the problems themselves, and rise the availability and productivity of the facility. Saying this, the importance of having optimally made problem-cause lists is expressed. Better these lists are made, higher quality outputs come out of the analysis, more appropriate tactics and technologies are employed, and larger number of problem-causes will be prevented in the future. Knowing specific electrical or mechanical problem-causes in a facility or plant, maintenance technicians can be equipped with adequate tools to predict and prevent potential failures in advance. For example, if there has been a problem-cause of overload in a specific station of a facility, proper tools can be utilized to inspect that specific station and its machinery for overloads on a regular basis. Tables 13 and 14 are structured in a way to indicate the most degraded stations based on particular predefined problems. For instance, from the below tables it is known that station S07 is the most degraded station by the electrical problems which were caused by abrasion, while the station S01 is the most degraded station by the mechanical problems which were caused again by abrasion. This information facilitates a maintenance planner with better scheduling routine inspections in stations S01 and S14 to identify cases of abrasions. Moreover, a maintenance analyst may identify the best tools and methods to spot abrasion as a critical electrical and mechanical cause.

Table 13 The most electrically degraded stations of P1 facility based on electrical problem-causes from 01.07.05 to 30.06.09

Code	Electrical Problem-Cause	Total No. of Incurrence	Station(No. of Occurrence)	Most Degraded Station
1001	Crash	20	GWM(**3**),V01(**5**),S01(**1**),S02(**2**),S03(**1**),S06(**1**),S10(**1**),S12(**1**),S14(**1**),S17(**1**),S18(**1**),S18A(**1**),Gen.(**1**)	**V01**
1002	Abrasion	168	GWM(**4**),V01(**8**),V02(**8**),V04(**4**),V05(**3**),S01(**13**),S02(**14**),S03(**16**),S05(**4**),S06(**9**),S07(**17**),S09(**2**),S10(**10**),S11(**5**),S12(**6**),S12A(**2**),S13(**3**),S14(**10**),S15(**5**),S16(**6**),S17(**5**),S18(**4**),A01(**3**),FB01(**1**),Gen.(**6**)	**S07**
1003	Overload	8	GWM(**1**),V01(**2**),V02(**1**),V04(**1**),S15(**2**),FB01(**1**)	**V01,S15**
1004	No Lubrication	0	NA	NA
1005	No Ventilation	0	NA	NA
1006	No Cooling	0	NA	NA
1007	No Medium	2	GWM(**1**),S03(**1**)	**GWM,S03**
1008	Operating Fault	10	S01(**1**),S02(**1**),S07(**1**),S10(**1**),S14(**3**),S17(**2**),Gen.(**1**)	**S01**
1009	Rupture	53	V01(**3**),V02(**1**),V04(**2**),S01(**5**),S03(**3**),S06(**18**),S07(**11**),S12(**2**),S14(**1**),S15(**1**),S16(**1**),S18A(**1**),A01(**1**),Gen.(**3**)	**S06**
1010	Wrong Material	1	S03(**1**)	**S03**
1011	Manufacturer Fault	15	S01(**5**),S02(**2**),S05(**1**),S14(**2**),S18(**1**),A01(**3**),Gen.(**1**)	**S01**
1012	Unknow able Cause	180	GWM(**4**),V01(**7**),V02(**9**),V04(**5**),V05(**4**),S01(**5**),S02(**15**),S03(**11**),S05(**4**),S06(**2**),S07(**7**),S10(**14**),S11(**4**),S12(**3**),S12A(**2**),S13(**6**),S14(**27**),S15(**7**),S16(**2**),S17(**7**),S18(**4**),S18A(**1**),A01(**10**),EDV1(**5**),FB01(**3**),Gen.(**12**)	**S14**
1013	Misalignment	4	GWM(**2**),S02(**1**),S14(**1**)	**GWM,S03**
1014	Miscelleneous	42	GWM(**3**),V01(**2**),V02(**1**),V04(**1**),V05(**1**),S01(**5**),S02(**2**),S03(**5**),S05(**3**),S06(**1**),S07(**1**),S10(**3**),S11(**1**),S13(**1**),S15(**1**),S17(**3**),S18(**1**),EDV1(**4**),FB01(**1**),Gen.(**2**)	**S01,S05**

Table 14 The most mechanically degraded stations of P1 facility based on mechanical problem-causes from 01.07.05 to 30.06.09

Code	Mechanical Problem-Cause	Total No. of Incurrence	Station(No. of Occurrence)	Most Degraded Station
1001	Crash	53	GWM(**3**),V01(**3**),V02(**1**),V04(**2**),V05(**1**),S01(**22**),S02(**4**),S03(**1**),S14(**2**),S15(**1**),S16(**1**),S17(**1**),S18(**2**),S18A(**2**),A01(**1**),FB01(**1**),Gen.(**5**)	**S01**
1002	Abrasion	822	GWM(**14**),V01(**22**),V02(**1**),V04(**10**),V05(**6**),S01(**185**),S02(**85**),S03(**24**),S05(**1**),S06(**94**),S07(**68**),S09(**4**),S10(**11**),S11(**5**),S12(**3**),S12A(**6**),S13(**8**),S14(**56**),S15(**19**),S16(**24**),S17(**11**),S18(**4**),S18A(**5**),A01(**18**),EDV1(**2**),FB01(**62**),Gen.(**73**)	**S01**
1003	Overload	17	GWM(**2**),S01(**3**),S02(**1**),S06(**2**),S07(**3**),S14(**2**),S15(**1**),S17(**1**),Gen.(**2**)	**S01,S07**
1004	No Lubrication	2	S01(**1**),FB01(**1**)	**S01,FB01**
1005	No Ventilation	1	GWM(**1**)	**GWM**
1006	No Cooling	0	NA	NA
1007	No Medium	5	GWM(**2**),S10(**1**),S14(**1**),S15(**1**)	**GWM**
1008	Operating Fault	39	GWM(**1**),V01(**2**),V02(**1**),V04(**1**),S01(**12**),S02(**9**),S03(**1**),S06(**2**),S10(**1**),S11(**1**),S14(**3**),S15(**1**),S17(**1**),FB01(**1**),Gen.(**2**)	**S01**
1009	Rupture	107	GWM(**2**),V01(**4**),V02(**1**),V04(**2**),V05(**3**),S01(**21**),S02(**7**),S05(**1**),S06(**12**),S07(**8**),S09(**2**),S10(**1**),S11(**2**),S12(**1**),S14(**6**),S15(**1**),S16(**2**),S17(**2**),S18(**1**),S18A(**1**),A01(**2**),FB01(**9**),Gen.(**16**)	**S01**
1010	Wrong Material	7	V01(**1**),S05(**1**),S06(**2**),S07(**1**),S14(**1**),FB01(**1**)	**S06**
1011	Manufacturer Fault	94	GWM(**1**),V01(**2**),V04(**2**),V05(**1**),S01(**48**),S02(**10**),S03(**4**),S05(**2**),S06(**1**),S07(**2**),S09(**3**),S10(**1**),S12A(**1**),S14(**1**),S15(**1**),S16(**7**),S17(**1**),S18(**1**),S18A(**1**),A01(**3**),FB01(**3**),Gen.(**4**)	**S01**
1012	Unknow able Cause	317	GWM(**7**),V01(**11**),V02(**5**),V05(**2**),S01(**46**),S02(**12**),S03(**4**),S05(**1**),S06(**47**),S07(**70**),S09(**3**),S10(**13**),S11(**2**),S13(**3**),S14(**22**),S15(**16**),S16(**8**),S17(**4**),S18(**2**),S18A(**4**),A01(**9**),EDV1(**1**),FB01(**7**),Gen.(**19**)	**S07**
1013	Misalignment	14	GWM(**1**),V02(**1**),V05(**1**),S01(**2**),S03(**1**),S05(**1**),S06(**1**),S07(**1**),S10(**2**),S11(**1**),S14(**1**),S18(**1**)	**S01,S10**
1014	Miscelleneous	83	GWM(**1**),V01(**1**),V02(**3**),V04(**6**),V05(**4**),S01(**14**),S02(**7**),S03(**4**),S06(**7**),S07(**2**),S09(**1**),S10(**3**),S12A(**1**),S13(**2**),S14(**3**),S16(**4**),S17(**1**),S18A(**2**),FB01(**6**),Gen.(**11**)	**S01**

It is also possible to go one step forward and to identify which types of problem-causes are more associated with which machinery objects. In other words, it is possible to identify the most degraded machinery objects based on a specific predefined problem-cause. This helps maintenance departments to know exactly the problem-causes related to specific objects and optimally utilize all of their resources to identify and eliminate them. Tables 15 and 16 show the most degraded machinery objects based on predefined electrical and mechanical problem-causes. For example, it can be easily seen that overload has been mostly the cause of electrical problems associated with measuring sensors and abrasion has been mostly the cause of mechanical problems linked to cylinders. It is indispensable to note that better the lists of electrical and mechanical problem-causes and also the machinery objects are made, better and more reliable is the resultant information out of the undertaken analyses. Knowing the most frequent problem-cause of a machinery object or the most frequent problem-cause incurring in a station of facility is priceless information that can be obtained from cause based failure analysis. Such information can be used widely by maintenance department to get use of the most appropriate condition monitoring techniques and nondestructive test for a particular facility or machinery object and also to prepare and schedule planned maintenance activities in the most effective way. The reliability of such information depends on how good such lists are designed and how often they have been correctly used. Here, the aim is to show the methodology and the information that can be obtained from such analyses.

Table 15 The most electrically degraded machinery objects in the P1 facility based on electrical problem-causes from 01.07.05 to 30.06.09

Code	Electrical Problem-Cause	Total No. of Occurrence	Machinery Object(No. of Occurrence)	Most Degraded Machinery Object(s)	
1001	Crash	19	0003(3),0011(2),0013(1),0014(1),0016(4),0017(2),0018(1),0019(1),0021(1),0023(1),0027(2)	0016	Cable/Wire
1002	Abrasion	153	0002(2),0003(3),0007(1),0008(6),0009(5),0010(1),0011(1),0014(1),0015(1),0016(49),0017(24),0018(9),0019(11),0020(8),0021(1),0023(11),0025(1),0026(11),0027(11),0028(1),0034(1),0035(1),0037(4)	0016	Cable/Wire
1003	Overload	7	0009(1),0016(1),0023(2),0026(2),0027(1)	0023,0026	Measuring Sensor,Gear Fastener
1004	No Lubrication	0	NA	NA	NA
1005	No Ventilation	0	NA	NA	NA
1006	No Cooling	0	NA	NA	NA
1007	No Medium	2	0009(1),0016(1)	0009,0016	Switch Cabinet,Cable/Wire
1008	Operating Fault	10	0001(1),0003(1),0009(1),0017(2),0023(3),0024(1),0026(1),0027(1)	0023	Measuring Sensor
1009	Rupture	49	0003(1),0016(34),0017(4),0018(1),0021(1),0023(3),0026(1),0027(4)	0016	Cable/Wire
1010	Wrong Material	1	0037(1)	NA	NA
1011	Manufacturer Fault	14	0008(1),0016(3),0017(1),0018(4),0019(3),0027(1)	0018	End/Proximity Switch
1012	Unknown Cause	168	0001(1),0003(5),0006(1),0008(3),0009(11),0010(1),0011(1),0012(3),0013(1),0014(1),0015(2),0016(13),0017(13),0018(4),0019(15),0020(5),0022(4),0023(35),0026(2),0027(37),0034(7),0037(2)	0027	Switching/Control Element
1013	Misalignment	4	0023(2),0027(2)	0023,0027	Measuring Sensor,Switching/Control Element
1014	Miscelleneous	42	0003(1),0008(1),0009(3),0010(1),0015(1),0016(4),0017(2),0018(2),0019(2),0020(3),0022(1),0023(2),0027(5),0034(1),0035(1),0037(13)	0027	Switching/Control Element

Table 16 The most mechanically degraded machinery objects in the P1 facility based on mechanical problem-causes from 01.07.05 to 30.06.09

Code	Mechanical Problem-Cause	Total No. of Occurrence	Machinery Objet(No. of Occurrence)	Most Degraded Machinery Object(s)	
1001	Crash	41	0003(3),0006(1),0011(7),0013(2),0014(1),0016(2),0017(7),0018(2),0019(1),0020(3),0023(1),0026(3),0027(2),0037(6)	0011,0017	Protective Shield,Switch/Button
1002	Abrasion	353	0001(2),0003(3),0006(5),0007(24),0008(2),0010(18),0011(12),0012(7),0013(27),0014(40),0015(42),0016(20),0017(14),0018(2),0019(3),0023(6),0024(21),0026(11),0027(22),0028(2),0035(1),0037(69)	0015	Cylinder
1003	Overload	13	0001(2),0003(1),0007(1),0011(1),0026(2),0030(1),0037(5)	0001,0026	Exhaust,Gear Fastener
1004	No Lubrication	2	0003(1),0007(1)	0007	Pump
1005	No Ventilation	1	0024(1)	0024	Filter
1006	No Cooling	0	NA	NA	NA
1007	No Medium	5	0007(1),0015(2),0024(1),0027(1)	0015	Cylinder
1008	Operating Fault	14	0003(1),0006(3),0007(1),0010(1),0014(1),0022(1),0023(2),0024(1),0026(1),0027(1),0037(1)	0006	Sliding Carriage
1009	Rupture	61	0006(3),0009(1),0011(5),0013(11),0014(5),0015(7),0016(7),0017(3),0018(1),0019(3),0023(1),0024(2),0027(1),0037(11)	0013	Conveyer Belt
1010	Wrong Material	2	0014(1),0023(1)	0014,0023	Valve,Measuring Sensor
1011	Manufacturer Fault	26	0008(1),0011(9),0012(1),0016(2),0017(1),0018(1),0019(2),0026(2),0027(4),0037(3)	0011	Protective Shield
1012	Unknown Cause	152	0001(1),0003(7),0006(1),0007(12),0010(6),0011(9),0012(4),0013(5),0014(14),0015(22),0016(7),0017(3),0018(5),0019(2),0023(14),0024(1),0026(4),0027(13),0030(2),0037(20)	0015	Cylinder
1013	Misalignment	13	0003(1),0013(2),0014(4),0023(3),0027(1),0028(1),0035(1)	0014	Valve
1014	Miscelleneous	65	0002(1),0006(2),0007(1),0010(1),0011(6),0013(2),0014(3),0016(1),0017(1),0023(1),0024(1),0025(1),0026(1),0027(6),0031(1),0037(36)	0011,0027	Protective Shield,Switching/Control Element

5.6 Statistical Problem Cause Analysis

Another step towards accomplishing a comprehensive statistical failure analysis is to undertake a statistical problem cause analysis. Such an analysis can be made by identifying all the causes of particular electrical and mechanical problems and then the most frequent cause(s) of each problem. Indeed, this helps learning more about the nature of problems and how they occur. Statistical problem cause analysis is a precious tool to know the most frequent or incurred problem-causes and then try to eliminate or prevent them to be formed and cause a problem. Tables 17 and 18 show the most incurred causes of predefined electrical and mechanical problems in the P1. Having a glance over the two tables it is seen that the most frequent causes of most of problems is either abrasion or unknown. It is extremely essential to underline that the better these lists are made and used; more precise and reliable will be the results of such analyses. In this report the aim has been to show the statistical tools and their usage and the indispensable information they can provide.

Table 17 The most incurred electrical problem-causes in the P1 facility from 01.07.05 to 30.06.09

Code	**Electrical Problem**	**Total No. of Occurrence**	**Electrical Problem-Cause(No. of Occurrence)**	**Most Incurred Problem-Cause(s)**	
CE01	Noise Emission	1	1002(**1**)	**1002**	Abrasion
CE02	Heat Generation	1	1012(**1**)	NA	NA
CE03	Spark Formation	1	1012(**1**)	NA	NA
CE04	Isolation Damage	10	1001(**1**),1002(**5**),1003(**1**),1009(**1**),1011(**1**),1012(**1**)	**1002**	Abrasion
CE05	No Function	314	1001(**11**),1002(**102**),1003(**2**),1007(**1**),1008(**7**),1009(**33**),1011(**9**),1012(**121**),1013(**2**),1014(**26**)	**1002**	Abrasion
CE06	Light Outfall	5	1001(**1**),1002(**2**),1012(**1**),1014(**1**)	**1002**	Abrasion
CE07	Control Indicator Failure	53	1002(**12**),1003(**1**),1007(**1**),1008(**2**),1009(**2**),1011(**5**),1012(**30**)	**1002**	Abrasion
CE08	Partial Damage	66	1001(**5**),1002(**35**),1003(**1**),1009(**14**),1012(**10**)	**1002**	Abrasion
CE09	Deformation	3	1002(**1**),1009(**1**),1013(**1**)	**1002,1009,1013**	Abrasion,Rupture,Misalignment
CE10	Blockade	13	1001(**1**),1002(**2**),1003(**3**),1009(**1**),1012(**6**)	**1003**	Overload
CE11	Smoke Emission	2	1012(**1**),1014(**1**)	NA	NA
CE12	Miscelleneous	34	1001(**1**),1002(**8**),1009(**1**),1010(**1**),1012(**8**),1013(**1**),1014(**14**)	**1002**	Abrasion

Table 18 The most incurred mechanical problem-causes in the P1 facility from 01.07.05 to 30.06.09

Code	**Mechanical Problem**	**Total No. of Occurrence**	**Mechanical Problem-Cause(No. of Occurrence)**	**Most Incurred Problem-Cause**	
3001	Noise Emission	8	1002(**4**),1004(**1**),1012(**2**),1013(**1**)	**1002**	Abrasion
3002	Deformation	184	1001(**6**),1002(**152**),1003(**1**),1008(**5**),1009(**2**),1011(**17**),1012(**1**)	**1002**	Abrasion
C003	Leakage	125	1001(**2**),1002(**94**),1003(**2**),1008(**1**),1009(**5**),1010(**1**),1011(**1**),1012(**16**),1013(**1**),1014(**2**)	**1002**	Abrasion
C004	No Function	275	1001(**3**),1002(**122**),1003(**1**),1008(**4**),1009(**18**),1010(**2**),1011(**6**),1012(**114**),1013(**1**),1014(**4**)	**1002**	Abrasion
C005	Heat Generation	0	NA	NA	NA
C006	Faulty Production	23	1002(**4**),1008(**2**),1010(**2**),1011(**13**),1012(**2**)	**1011**	Manufacturer Fault
C007	Partial Damage	432	1001(**36**),1002(**235**),1003(**7**),1008(**19**),1009(**69**),1011(**13**),1012(**49**),1014(**4**)	**1002**	Abrasion
C008	Smoke Emission	1	1002(**1**)	**1002**	Abrasion
C009	Reduced Function	420	1001(**2**),1002(**197**),1003(**2**),1004(**1**),1005(**1**),1007(**5**),1008(**7**),1009(**10**),1010(**2**),1011(**44**),1012(**128**),1013(**10**),1014(**10**)	**1002**	Abrasion
C010	Blockade	23	1001(**4**),1002(**10**),1003(**3**),1008(**1**),1009(**1**),1012(**4**)	**1002**	Abrasion
C011	Miscelleneous	70	1002(**3**),1009(**2**),1012(**2**),1013(**1**),1014(**62**)	**1002**	Abrasion

5.7 Time Based Maintenance Analysis

The time based maintenance analysis (TBMA) is done by determining the absolute number of hours spent on repair and reactive maintenance (R&M) of a facility. This can be carried out for every station, damaged equipment and machinery objects, and each problem occurred in a facility during a definite period of time. When a failure occurs, a notification is sent to maintenance department, an order is placed in the system and one more technicians are sent to the site to fix the problem. After fixing the problem, each technician sends a completion confirmation based on which the time spent to fix the problem is calculated. This is the absolute time on the clock from the moment a technician is sent to the site till the time the problem is fixed and the machinery is back to the service. For example, there can be three technicians who were sent to fix a problem and it took from 1 to 4 p.m. to repair the damaged machinery and put it back in service. In this case, the absolute time spent on repair and maintenance of that particular machinery is 3 hours while the total men-hours can be up to 9. The time used to undertake a TBMA is the absolute time took to repair a machine or fix a problem not the total men-hours spent on that. It is so, as the aim of TBMA is not the cost calculation but the determination of number of hours a station or a machine has been out of service because of a particular problem.

The absolute time spent on the repair and reactive maintenance is indeed an indicator of availability of particular machinery plus a measure of variability of some attributes associated with the criticality degree. For example, if station X has the highest criticality in September with 100 occurred problems and 200 R&M hours, and the lowest availability in April with 300 R&M hours and 50 occurred problems, it does not only mean that in September the station may require more spare parts or in April it pesters the production twice more but also it can provide some advance information when it is combined with the result of other analyses. For instance, if the occurred problems and the damaged objects in station X are more or less similar, such information can be used as a performance measure of maintenance department or technicians. If the damaged objects are quite different, the information provided by TBMA denotes maintainability degree of those objects [334]. In case the problems are considerably different but the objects are similar, such information signifies the time and maintenance resources required to fix those particular problems.

The TBMA can be started by identifying the number of hours spent on repair and maintenance of different stations of a facility within a definite period of time. It is vital to know if a station has remained the most R&M time consuming station for long period of time or there have been some efforts resulting in the status change of that station. Figure 64 illustrates the change of number of R&M hours spent in each station of the P1 facility during four successive anni from 01.07.2005 to 30.06.2009. In this period of time, the most R&M time consuming station of P1 facility has been S01 in general, with required 495 R&M hours. However, this status has been given to the station S06 in the last annum with required 116.5 R&M hours in comparison to 74.5 hours for the station S01. During the same period of time, S12 has been the least R&M time consuming station of the P1 facility. It can be observed that some stations like S01, S02 and S07 have become less and less R&M time consuming while some such as GWM, S03 and S10 have become more R&M time consuming in the last annum.

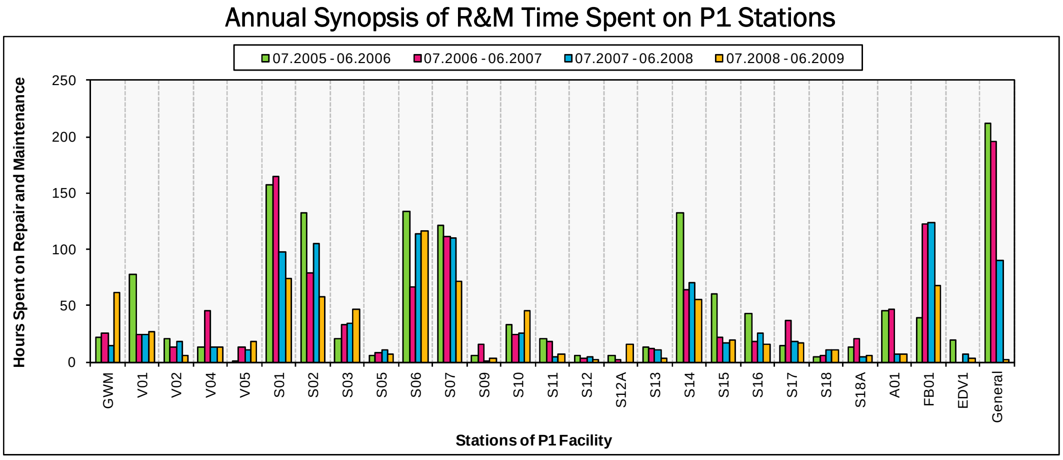


Figure 64 Number of hours spent on repair and maintenance in the P1 stations in annual cycles from 01.07.05 to 30.06.09.

Figure 65 indicates how significant the R&M time consumption of each station is. The figure shows the total time spent on repair and maintenance in each station of P1 facility between 01.07.2005 and 30.06.2009. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total R&M hours in P1 facility which counts for 4302.5 hours in the mentioned period. With some approximations this figure stands for 4302.5 hours of unavailability in four anni or roughly 1076 hours of unavailability per annum. On average, each station of the P1 facility has required 3.3 R&M hours per month or nearly 10 R&M hours per quarter within the studied period. From 01.07.2005 to 30.06.2009, approximately 60% of the total repair and maintenance time has been spent on the facility in general and for the stations S01, S02, S06, S07 and FB01, while roughly 30% spent for the stations GWM, S03, S10, S14, S15, S16, S17, A01 and V01.

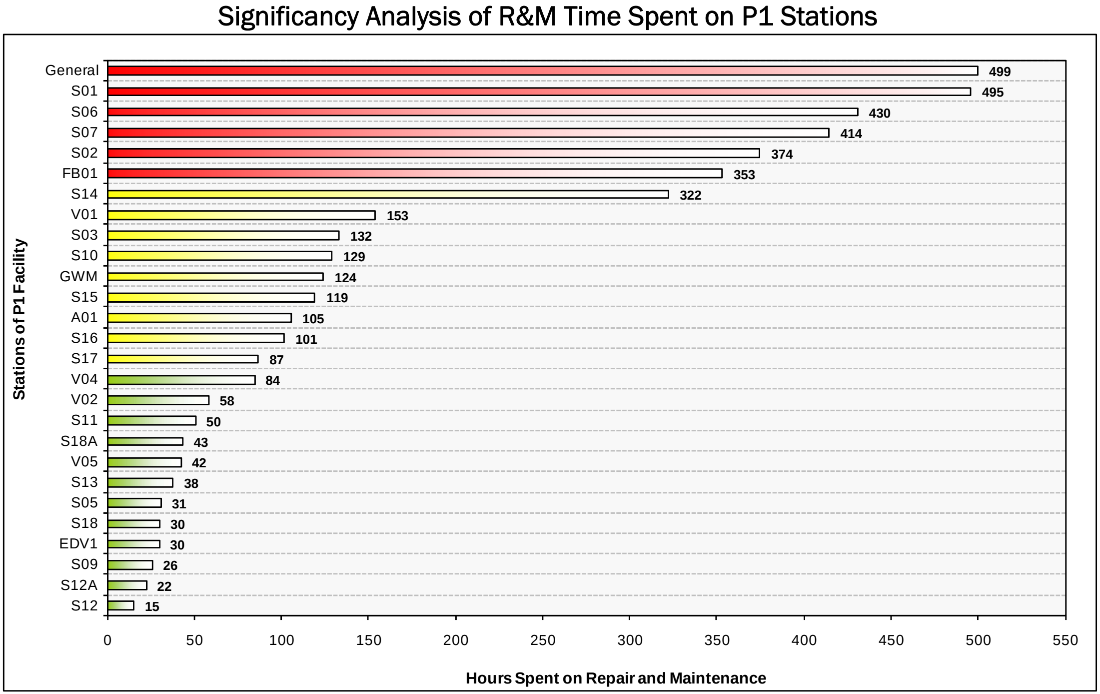


Figure 65 Number of hours spent on repair and maintenance in the P1 stations from 01.07.05 to 30.06.09; there is an approximate multi-colored classification of 60%, 30% and 10% of the total number of hours.

Besides, using the same data the most and the least R&M time consuming month of the year for each station can be identified. Basically, these are the months in which the stations have had the longest and shortest repair and maintenance time respectively. Such information facilitates the maintenance and production departments with an overview of the availability of different stations. For instance, for the station GWM, the most R&M time consuming month has been March with associated 8.6 hours on average. For the same station the least R&M time consuming month has been August with only 0.5 hour on average. The same rule applies for the whole facility as well. The most R&M time consuming month for the P1 facility has been September with recorded 126.5 R&M hours on average and the least R&M time consuming month is known to be June with associated 66.7 R&M hours on average. In a similar way the most R&M time consuming quarter for P1 facility has been the 1st quarter with 301.4 R&M hours on average and the least time consuming quarter of the year is seen to be the 2nd quarter with 227.3 R&M hours on average.

The variation of total hours spent on repair and maintenance in each station of a facility with respect to particular periods of time carries considerable important information as well. Figure 66, in the next page, presents the variation of total repair and maintenance hours in different stations of the P1 facility with respect to the quarter in which they were spent. As an example, S14 has consumed more R&M time in the 1st quarters while S02 has devoured more time for its repair and maintenance in the 3rd quarters. Indeed, the timely variation of total hours spent on repair and maintenance of different stations of a facility can be plotted on a monthly basis as well. Figure 67 represents such a monthly variation and can be employed to simply show the most R&M time consuming months for the stations of P1 facility. For instance, the most R&M time consuming month of a year for the station V04 can easily be identified as October. Such information is indispensable for both production and maintenance planning in addition to knowing the performance and characteristics of each station.

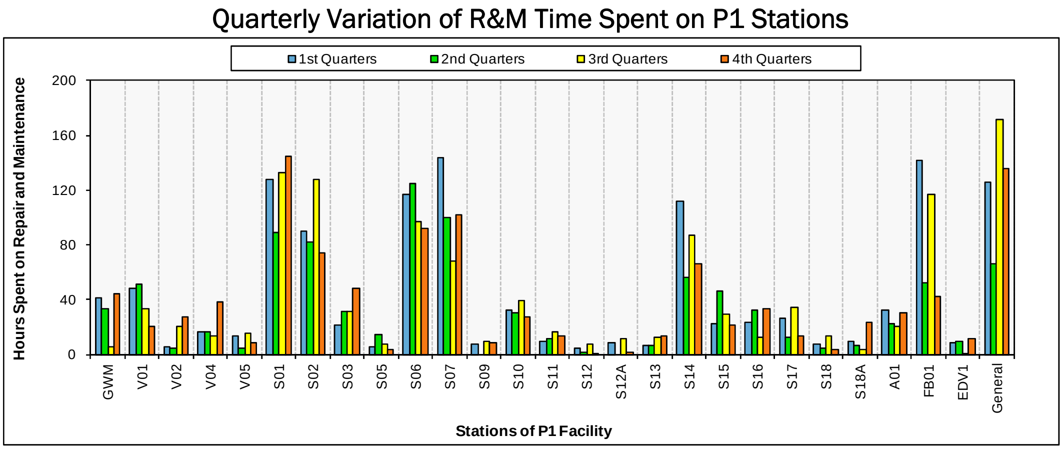


Figure 66 Number of hours spent on repair and maintenance in the P1 stations with respect to the quarter of occurrence from 01.07.05 to 30.06.09

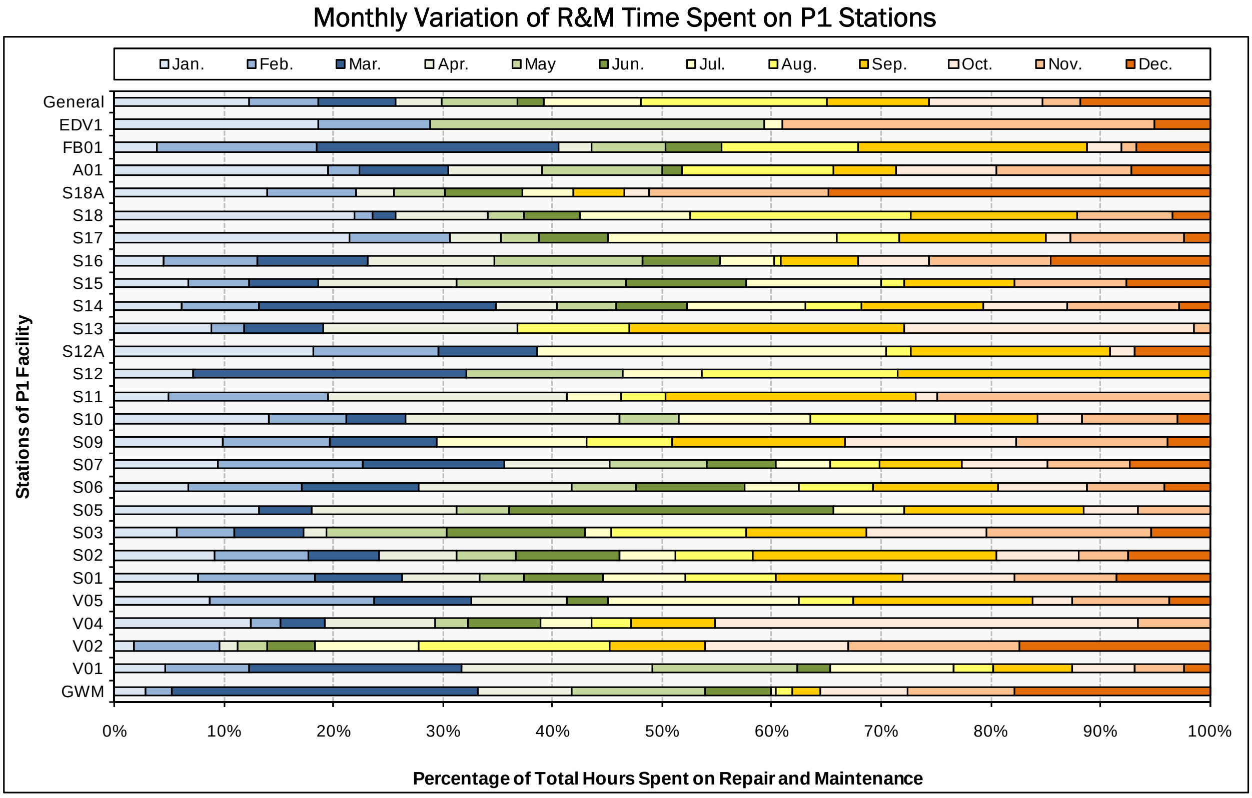
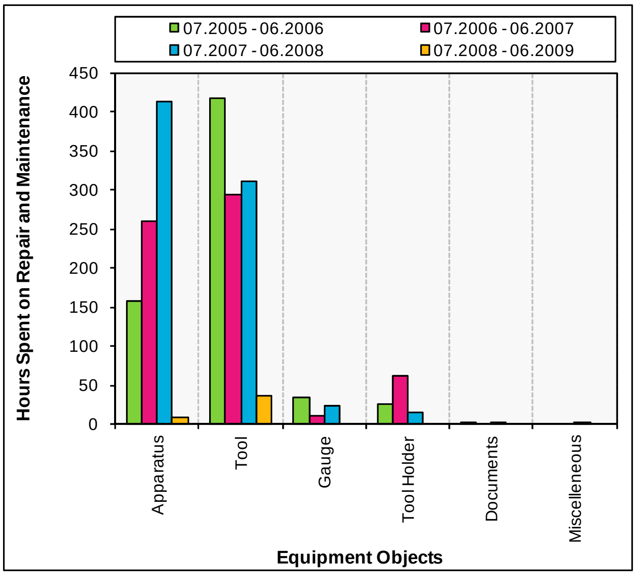


Figure 67 Percentage of total hours spent on repair and maintenance in the P1 stations with respect to the month of occurrence from 01.07.05 to 30.06.09

The next step in time based maintenance analysis is to determine the total time spent for repair and maintenance of different machinery in a facility within a definite period of time. As previously mentioned the objects or parts are divided into two groups in the SAP system of TRW-Schalke, equipment objects and machinery objects. Beginning with the equipment objects, it is important to know if an equipment object has remained the most R&M time consuming one for long period of time or there have been some annual changes.

Figure 68, in the next page, presents the change of total repair and maintenance time of different equipment objects in the P1 facility during four successive anni from 01.07.2005 to 30.06.2009. In this period of time, the most R&M time consuming equipment object has been ‘tool’ in general and also in the last annum, with required 1060 and 37 R&M hours accordingly. However, between 01.07.2007 to 30.06.2008 this status was belong to the equipment category ‘apparatus’ with associated 412.5 R&M hours in comparison to 310.5 R&M hours required for the equipment category tool. During the same period of time, tool holders, gauges and documents have been less R&M time consuming equipment objects.


Annual Synopsis of R&M Time Spent on Damaged Equipment Objects in P1 Facility

It is vital to know if an equipment object has remained the most R&M time consuming object for long a period of time or there have been some efforts resulting in the status change of that equipment object. Dividing the studied period from 01.07.2005 to 30.06.2009 into four annual cycles helps undertaking such an analysis.

As the graph on the left clearly indicates, the most R&M time consuming equipment object in the P1 facility has been the 'tool'. This situation has been the same for 'apparatus' as the second R&M time consuming equipment object on the list. Nevertheless, as a positive indicator, the total hours spent for repair and maintenance of all the equipment objects have shown considerable decrease in the last annum. This denotes the higher availability of equipment objects from 01.07.2008 to 30.06.2009.

Essentially, the usefulness of the output of such an analysis can only be increased, if the classification of different equipment objects is made with optimal level of details.

Figure 68 Number of hours spent on repair and maintenance of damaged equipment objects in the P1 facility in annual cycles from 01.07.05 to 30.06.09

Figure 69 shows how significant the R&M time consumption of each equipment object is. The figure presents the total time spent on repair and maintenance for each equipment object in the P1 facility between 01.07.2005 and 30.06.2009. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total R&M hours spent on the damaged equipment objects, which counts for 2075 hours in the mentioned period. With some approximations this figure stands for 2075 hours of unavailability of equipment objects in four anni or roughly 519 hours of unavailability of those equipment objects. On average, each equipment object in the P1 facility has required 6.1 R&M hours per month or nearly 18.2 R&M hours per quarter within the studied period.

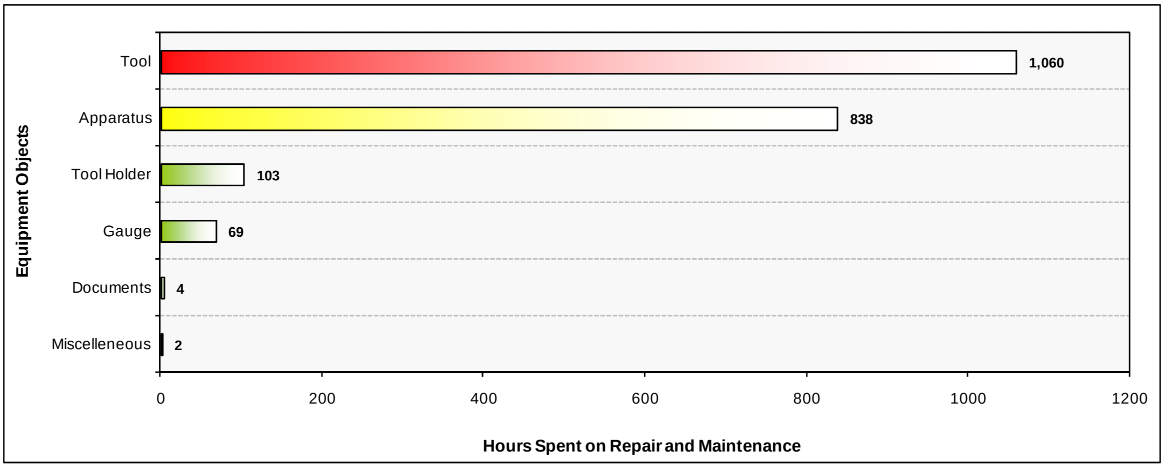
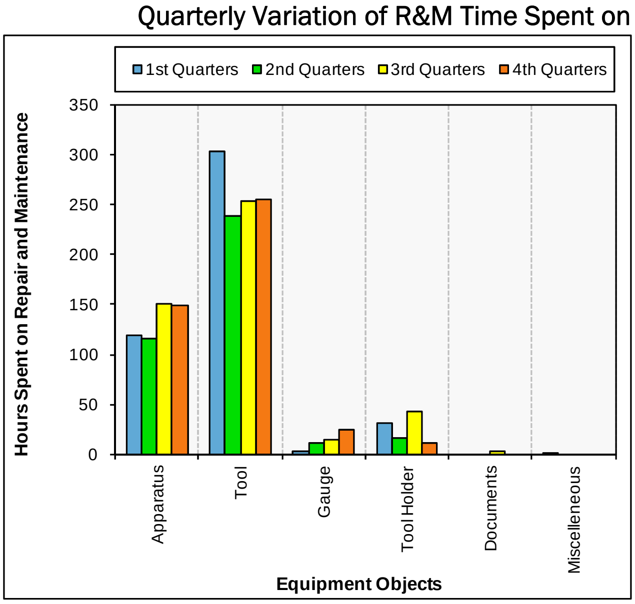

Significancy Analysis of R&M Time Spent on Damaged Equipment in P1 Facility

Figure 69 Number of hours spent on repair and maintenance of damaged equipment objects in P1 facility from 01.07.05 to 30.06.09.

With the same data the most and the least R&M time consuming month of the year for equipment object category can be identified. Such information facilitates the maintenance and production departments with an overview of the availability of different equipment objects. For instance, for the tools, the most R&M time consuming month has been March with associated 29.3 hours on average. For the same object the least R&M time consuming month has been December with 16 R&M hours on average. The same rule applies for the whole group of objects. The most R&M time consuming month for the equipment objects has been September with recorded 46.4 R&M hours on average and the least R&M time consuming month is known to be May with associated 28 R&M hours on average. Similarly the most and least R&M time consuming quarters for equipment objects have been the 1st and the 2nd quarters with respective 114.7 and 95.8 R&M hours on average.

Figure 70 shows the variation of total repair and maintenance hours of different equipment objects in the P1 facility with respect to the quarter in which they were spent. As an example, tools have consumed more R&M time in the 1st quarters while gauges have devoured more time for their repair and maintenance in the 4th quarters. Such a timely variation can be plotted on a monthly basis as done before. Figure 60 represents such a monthly variation and can be utilized to easily recognize the most R&M time consuming months for different equipment objects in the P1 facility. For instance, the most R&M time consuming month of a year for gauges can simply be identified as November.



Plotting variation of total required hours of repair and maintenance for the damaged equipment objects based on the quarter of incidence is helpful in determining the behavior and requirements of these equipment objects in different quarters of a year.

The graph on the left not only noticeably presents the most R&M time consuming equipment object in the P1 facility as the 'tool', but also it indicates that the most R&M time consuming quarter for this equipment object is the 1st and least R&M time consuming one is the 2nd quarter. These vary for the 'gauge' as the 4th and the 1st quarters respectively.

Knowing this can provide the maintenance managers and planners with essential information. They can obtain an overview of with what and how busy their workforce (i.e. maintenance technicians) have been and are expected to be in the future in different quarters of a year. Hence, they can effectively plan and utilize the resources in the plant.

Figure 70 Number of hours spent on repair and maintenance of damaged equipment objects in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

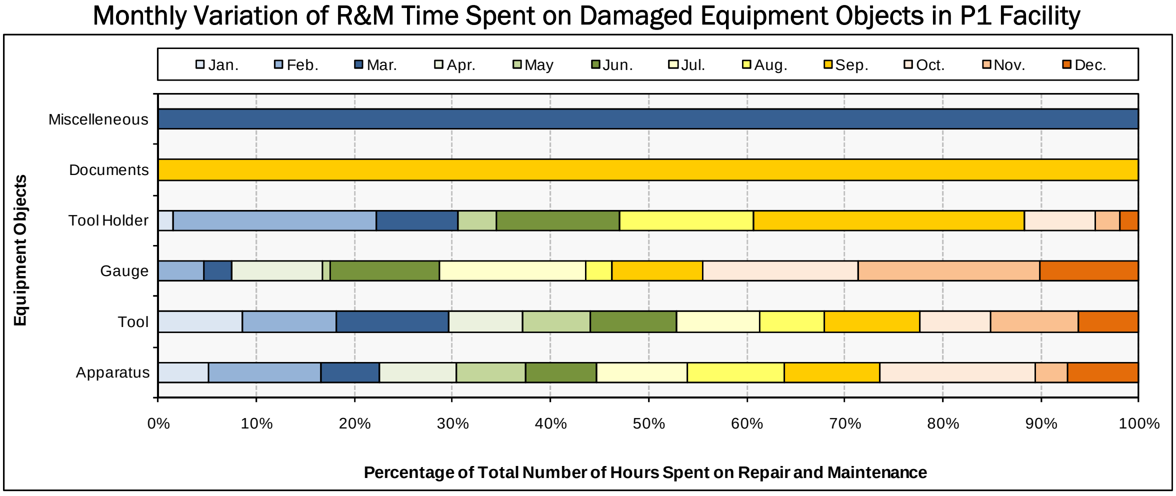


Figure 71 Percentage of total hours spent on repair and maintenance of damaged equipment objects in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

It is possible to identify the total time spent for repair and maintenance of different machinery objects in a facility within a definite period of time. It is important to know if a machinery object has remained the most R&M time consuming one for long period of time or there have been some annual changes. Figure 72, in the next page, indicates the change of total repair and maintenance time of different machinery objects in the P1 facility during four successive anni from 01.07.2005 to 30.06.2009. In this period of time, the most R&M time consuming machinery objects have been switching/control elements in general with required 249 R&M hours. However, taking into account the last annum only, this status should be given to the valves with required 52.5 R&M hours. During the overall studied period of time, cable/wire, valve, cylinder, conveyor belt and measuring sensor have been the most R&M time consuming machinery object categories after switching/control element. In the last annum, the total R&M time spent on miscellaneous machinery objects shows a drastic rise.

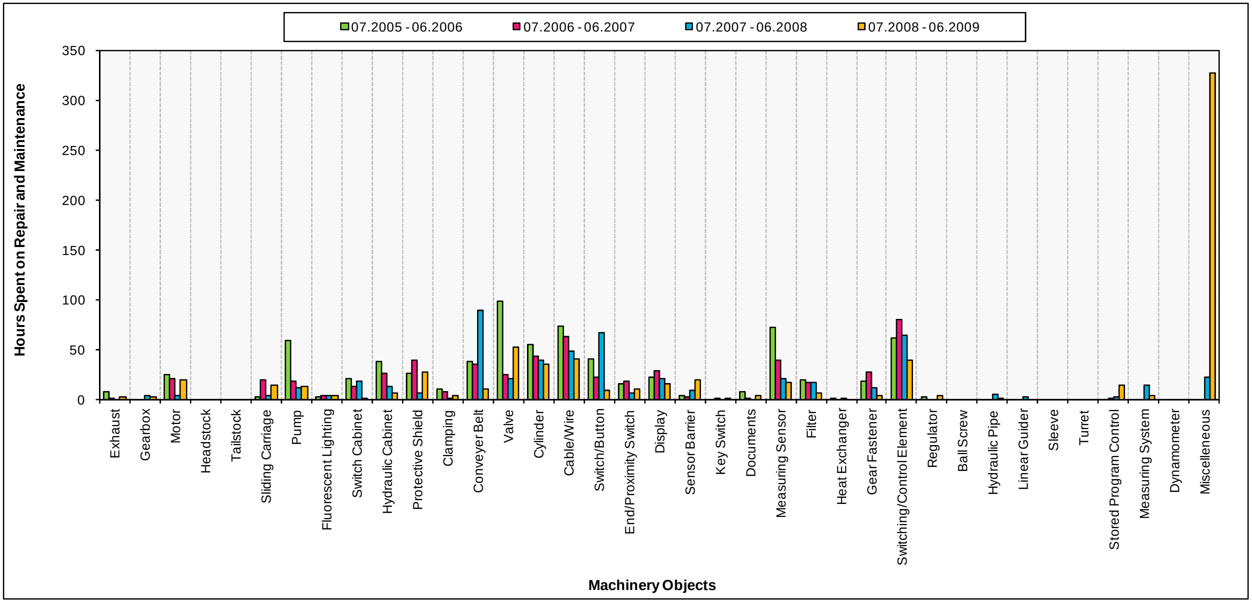


Figure 72 Number of hours spent on repair and maintenance of damaged machinery objects in the P1 facility in annual cycles from 01.07.05 to 30.06.09.

Figure 73 shows the significancy of the R&M time spent on the machinery objects in the P1 facility from 01.07.2005 to 30.06.2009 which on the whole counts for 2573.5 hours of unavailability of machinery objects in four anni or roughly 643.4 hours per annum due to repair and maintenance. On average, each machinery object has required 1.4 R&M hours per month or nearly 4.3 R&M hours per quarter.

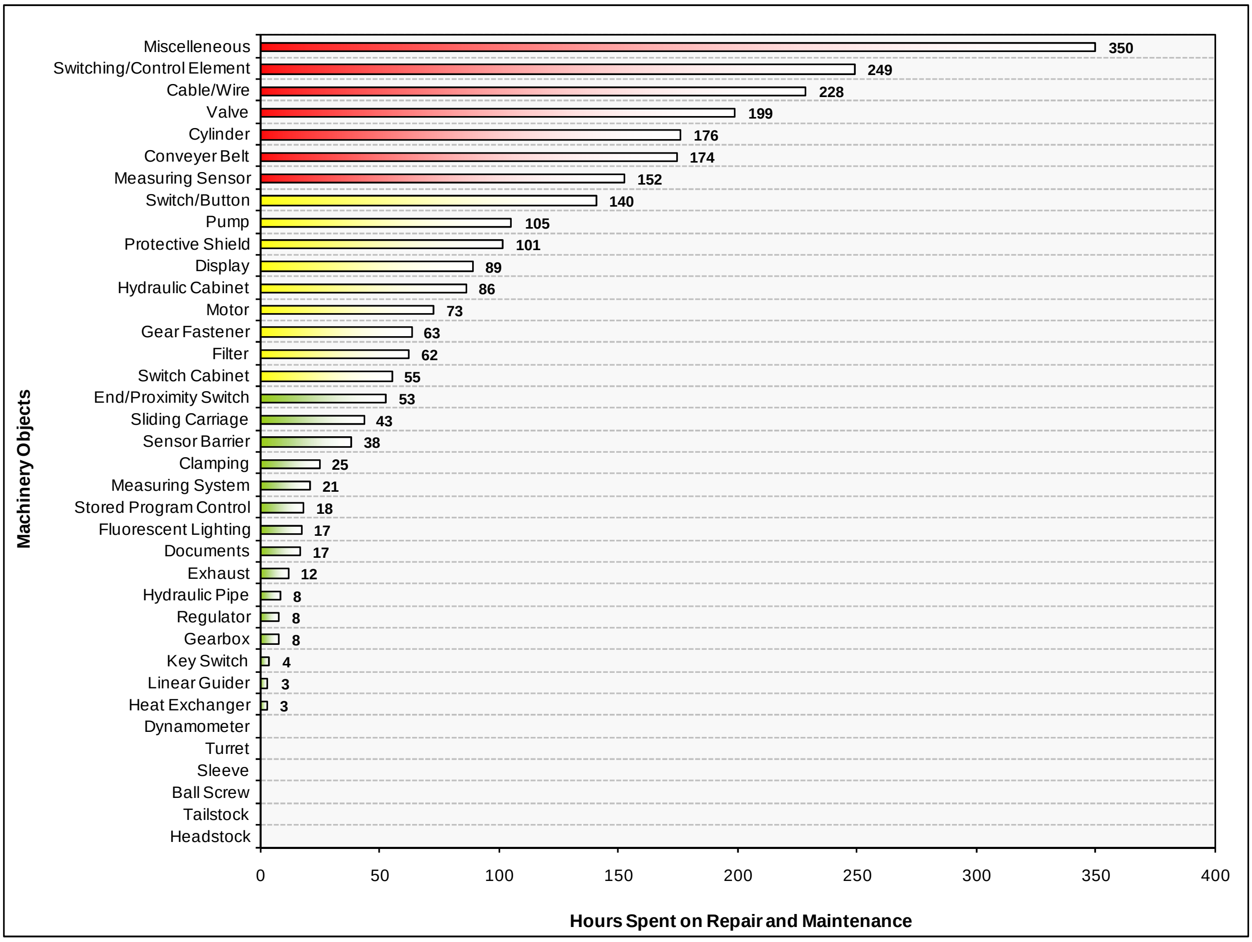


Figure 73 Number of hours spent on repair and maintenance of damaged machinery objects in the P1 facility from 01.07.05 to 30.06.09

Figure 74 shows the variation of total repair and maintenance hours of different machinery objects in the P1 facility with respect to the quarter in which they were spent. Figure 75 illustrates similar information but with a monthly variation and can be utilized to easily identify the most R&M time consuming months for different machinery objects in the P1 facility. For example, the most R&M time consuming month of a year for motors can simply be identified as April.

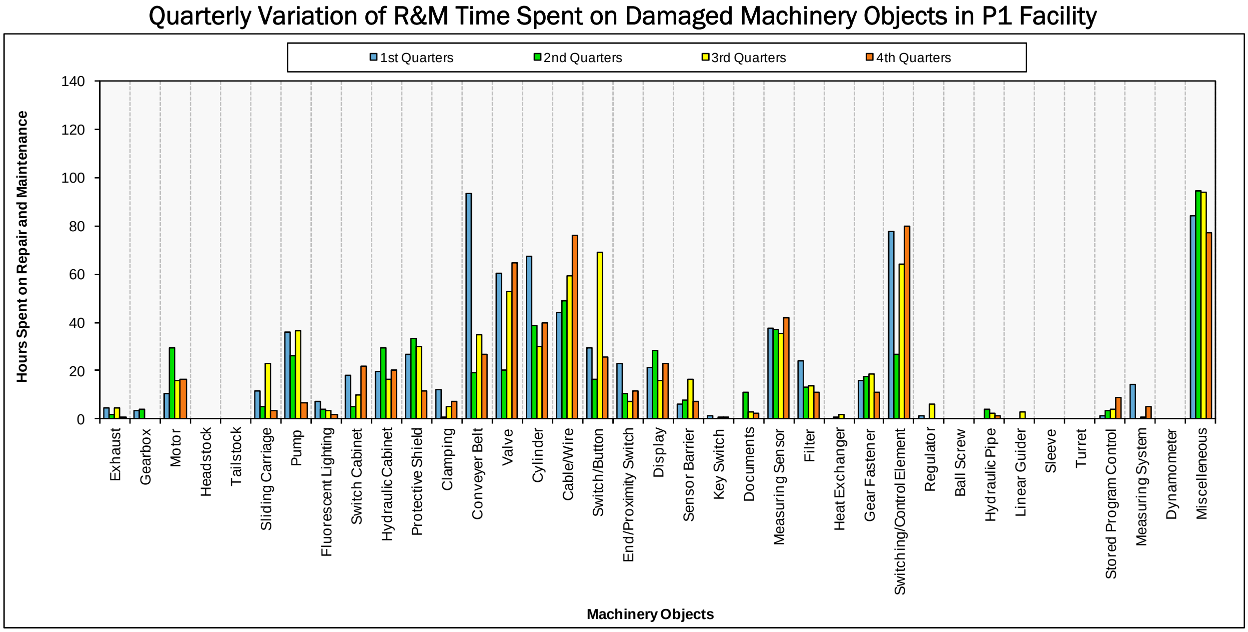


Figure 74 Number of hours spent on repair and maintenance of damaged machinery objects in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

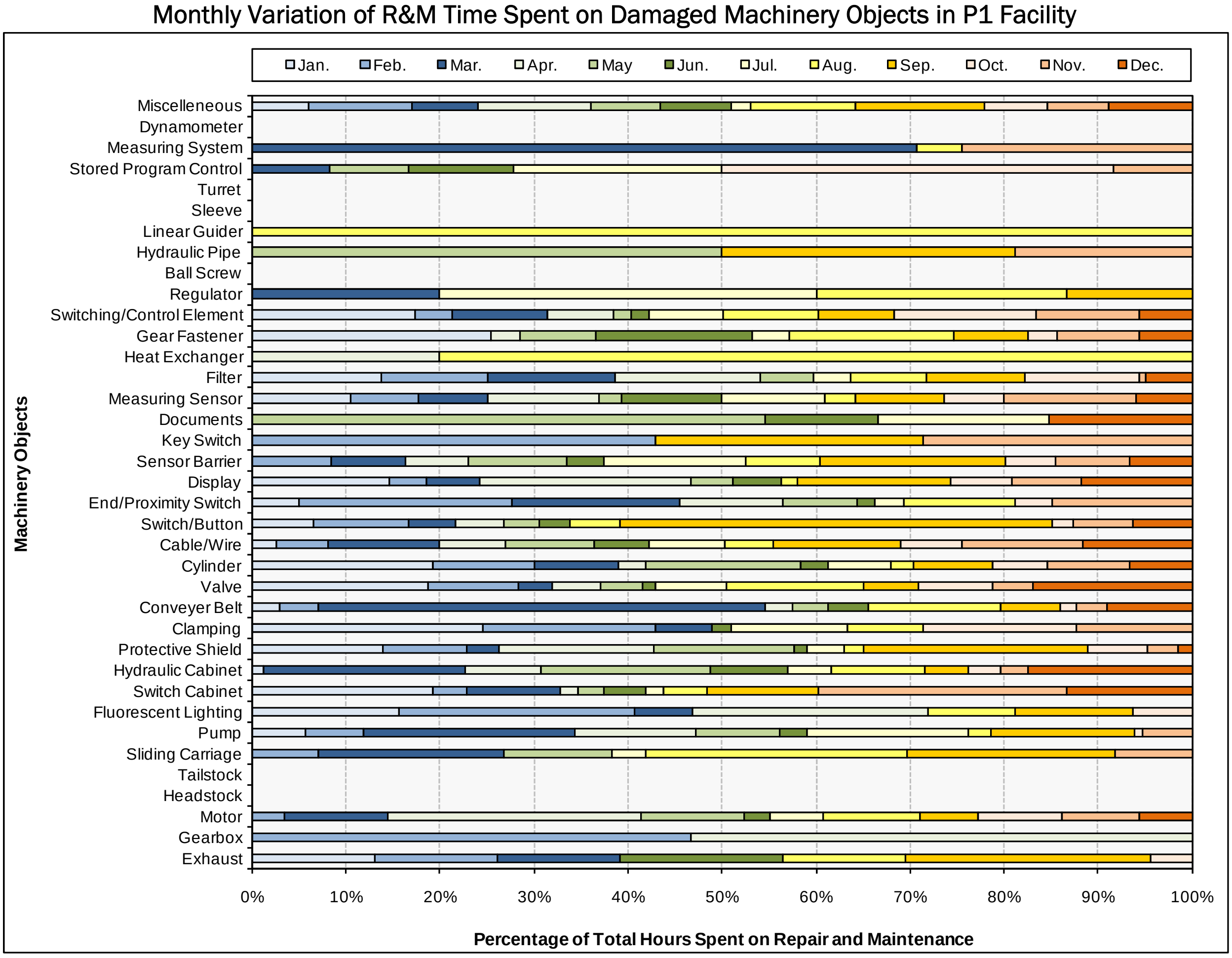
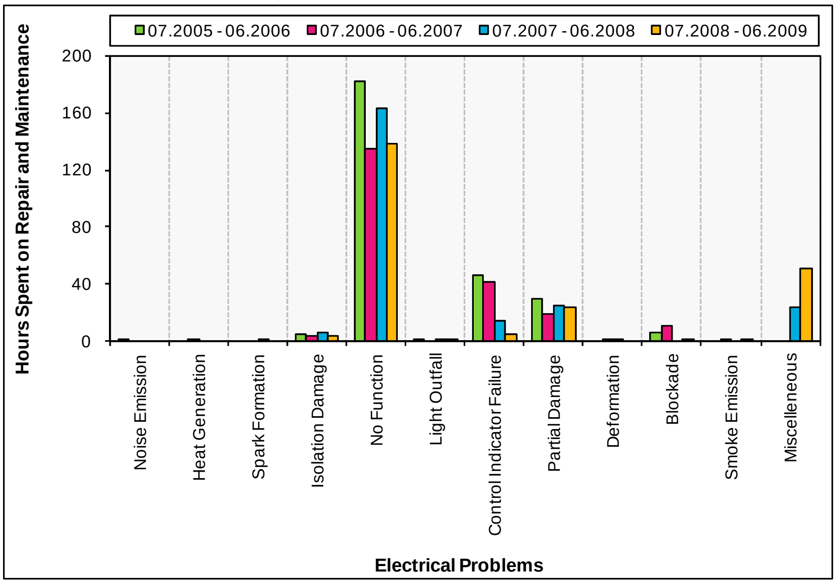


Figure 75 Percentage of total hours spent on repair and maintenance of damaged machinery objects in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

The next step is to discover the total repair and maintenance time spent to fix some particular problems. As it has been mentioned in previous parts of the report the problems are divided in two groups of electrical and mechanical problems in the information system of TRW-Schalke. Figure 76 indicates the change of total repair and maintenance time spent to fix different electrical problems occurred in the P1 facility during four successive anni from 01.07.2005 to 30.06.2009. Within this period, the most R&M time consuming electrical problem has been no function on the whole with required 618 R&M hours to be fixed.

Annual Synopsis of the R&M Time Spent to Fix Electrical Problems in P1 Facility



As the graph on the left shows, the most R&M time consuming electrical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been ‘no function’, ‘control indicator failure’ and ‘partial damage’ and for four successive anni on the whole. Nevertheless, the total R&M time spent to fix electrical problems which have been recorded as ‘miscellaneous’ shows a drastic rise in the last two anni from 01.01.2007 to 30.06.2009. This is not a favorable situation as it is not exactly known for which type of problems 74 hours of R&M time have been consumed in the last two anni. It should be again stated that the reliability and usefulness of the analysis can only be increased, if the problem classification is made optimally.

Figure 76 Number of hours spent on repair and maintenance of electrical problems occurred in the P1 facility in annual cycles within the time period from 01.07.05 to 30.06.09

Figure77 shows the significancy of the R&M time required to fix each electrical problem. The figure indicates the total repair and maintenance time spent to fix different electrical problems occurred in the P1 facility between 01.07.2005 and 30.06.2009. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total R&M hours in the P1 facility spent to fix electrical problems which counts for 949.3 hours in the mentioned period. With some approximations this figure stands for 949.3 hours of unavailability of the machinery in the P1 facility due to the electrical problems in four anni or roughly 237.3 hours of unavailability per annum. Within the studied period and on average, each predefined electrical problem occurred in the P1 facility has required 1.6 R&M hours per month or nearly 4.9 R&M hours per quarter to be fixed. From 01.07.2005 to 30.06.2009, approximately 60% of the total repair and maintenance time to fix electrical problems has been spent for the problem ‘no function’, while roughly 30% has been spent for the problem ‘control indicator failure’.

Significancy Analysis of the R&M Time Spent to Fix Electrical Problems in P1 Facility

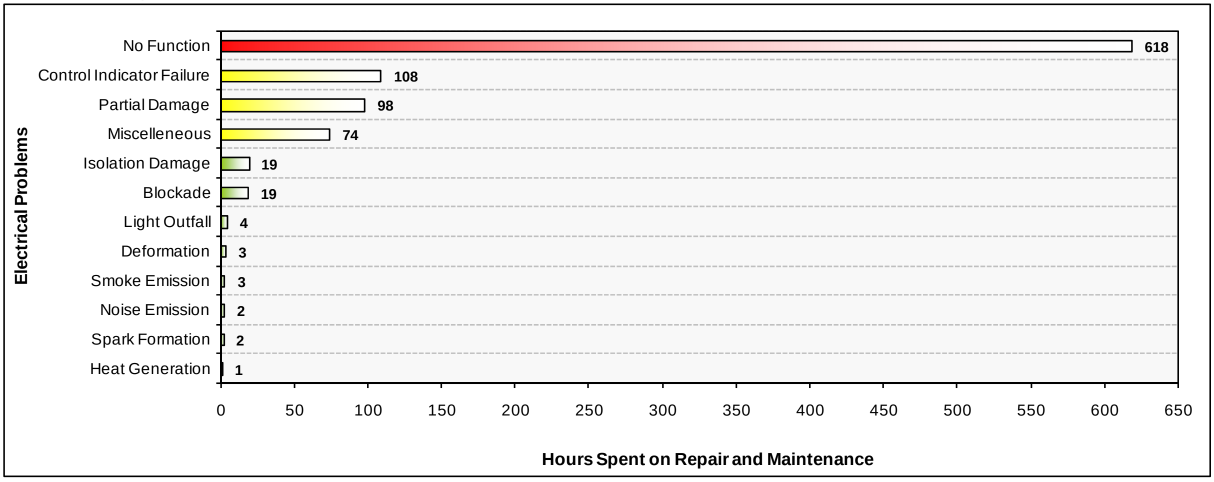
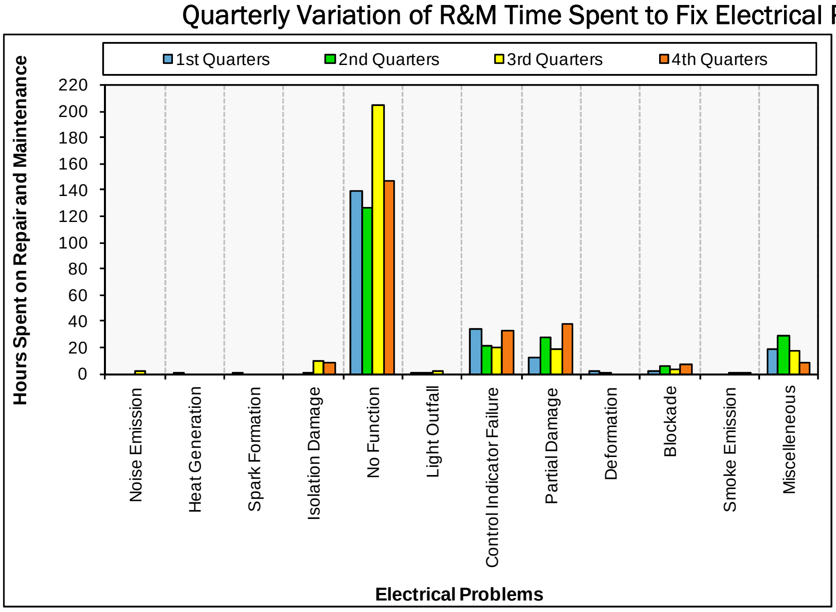


Figure 77 Number of hours spent on repair and maintenance of electrical problems occurred in the P1 facility from 01.07.05 to 30.06.09

The most and the least R&M time consuming month of a year to fix different electrical problems can be identified. This facilitates maintenance department with an overview of the most workforce consuming electrical problems and thus helps to decide for which maintenance techniques and technologies it has to invest. For instance, the most R&M time consuming month to fix the problem of control indicator failure has been November with associated 6.3 hours on average while the least R&M time consuming month has been July with 0.3 R&M hour on average. Overall, the most R&M time consuming month to fix the occurred electrical problems has been September with recorded 33.5 R&M hours on average and the least R&M time consuming month is known to be December with associated 11.8 R&M hours on average. Similarly the most and least R&M time consuming quarters to fix the occurred electrical problems have been the 3rd and the 2nd quarters with respective 70 and 53.2 R&M hours on average.

The variation of total repair and maintenance time spent to fix different electrical problems in a facility with respect to particular periods of time embraces substantial information as well. Figure 78 displays the variation of total repair and maintenance time spent to fix different electrical problems in the P1 facility with respect to the quarter in which they were occurred. For instance, partial damages have consumed more R&M time in the 4th quarters while indicator damages have devoured more time for their repair in the 3rd quarters. Such a timely variation can be plotted on a monthly basis. Figure 79 represents such a monthly variation and can be utilized to easily recognize the most R&M time consuming months for different electrical problems in the P1 facility.



As the graph on the left illustrates, the most R&M time consuming electrical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been ‘no function’, ‘control indicator failure’ and ‘partial damage’. While ‘no function’ has guzzled more R&M time in 3rd quarters, ‘control indicator failure’ and ‘partial damage’ have consumed more R&M time in 1st and 4th quarters respectively. Besides, while the R&M time consumed was the lowest in 3rd quarters for control indicator failures, for blockades it was the case in 1st quarters. An essential issue is the terms used to categorize the electrical problems: e.g. while ‘control indicator failure’ denotes perfectly a problem, ‘no function’ signifies the situation rather than specifying the problem itself.

Figure 78 Number of hours spent on repair and maintenance of electrical problems in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09.

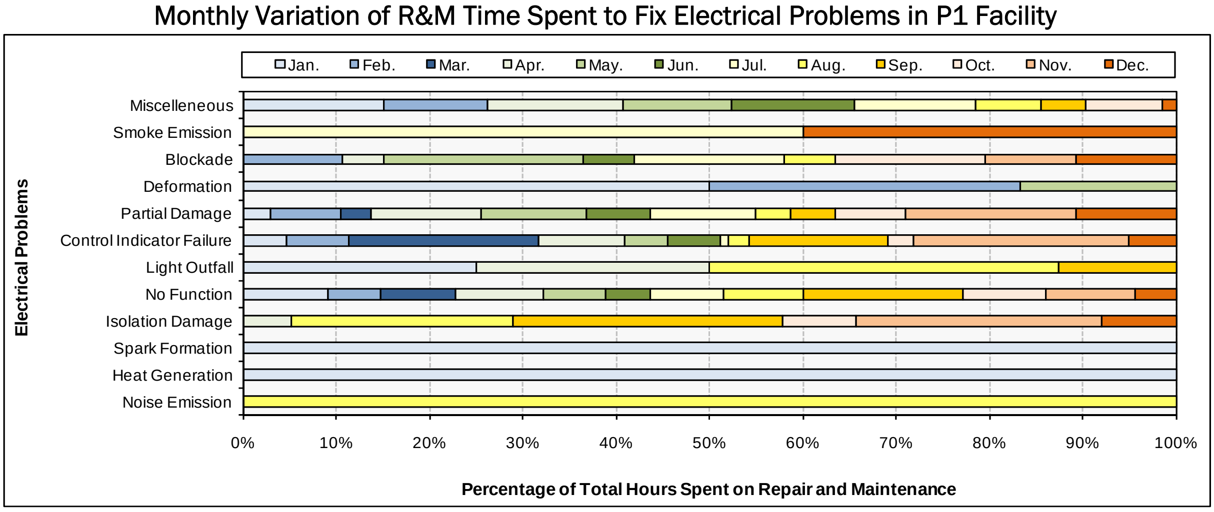
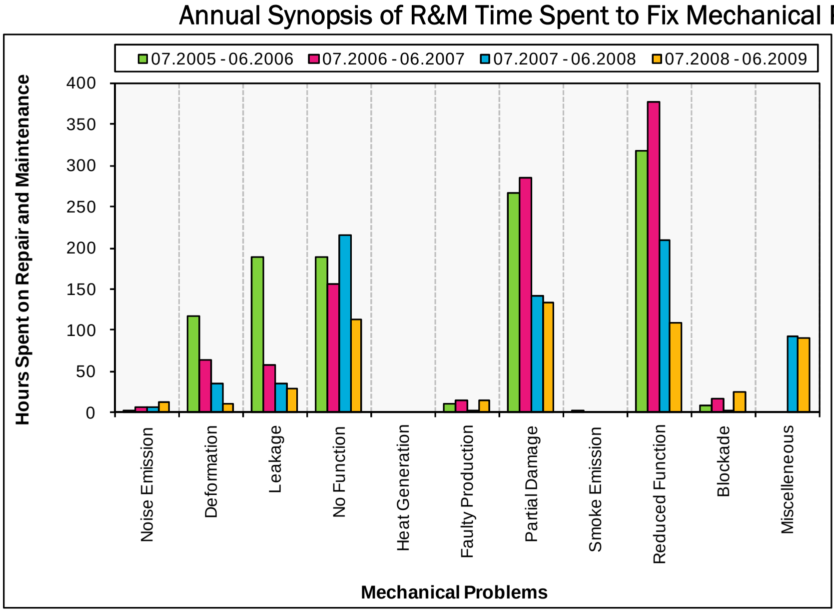


Figure 79 Percentage of total hours spent on repair and maintenance of electrical problems in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

The last step in undertaking a TBMA is to determine the total repair and maintenance time spent to fix particular mechanical problems. Figure 80 indicates the change of total repair and maintenance time spent to fix different mechanical problems occurred in the P1 facility during four successive anni from 01.07.2005 to 30.06.2009. Within this period, the most R&M time consuming mechanical problem has been reduced function on the whole with required 1014 R&M hours to be fixed. Taking into account the last annum only, this status has to be given to partial damage with required 133 R&M hours be fixed.



As the graph on the left indicates, the most R&M time consuming mechanical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been 'reduced function', 'partial damage' and 'no function' for four successive anni on the whole. Nonetheless, the total R&M time spent to fix mechanical problems which have been recorded as 'miscellaneous' shows a drastic rise in the last two anni from 01.01.2007 to 30.06.2009. This is not a favorable situation as it is not exactly known for which type of problems 184 hours of R&M time have been consumed in the last two anni. Again, it should be underlined that the reliability and usefulness of the analysis can only be raised, if the problem classification is made optimally.

Figure 80 Number of hours spent on repair and maintenance of mechanical problems occurred in the P1 facility in annual cycles within the time period from 01.07.05 to 30.06.09

Figure 81 shows the significancy of the R&M time required to fix each mechanical problem. The figure indicates the total repair and maintenance time spent to fix different mechanical problems occurred in the P1 facility between 01.07.2005 and 30.06.2009. The chart is colored in red, yellow and green denoting approximate 60%, 30% and 10% of the total R&M hours in the P1 facility spent to fix mechanical problems which counts for 3363.2 hours in the mentioned period. With some approximations this figure stands for 3363.2 hours of unavailability of the machinery in the P1 facility due to the mechanical problems in four anni or roughly 840.8 hours per annum. Within the studied period and on average, each predefined mechanical problem occurred in the P1 facility has required 6.4 R&M hours per month or nearly 19.1 R&M hours per quarter to be fixed. From 01.07.2005 to 30.06.2009, approximately 60% of the total repair and maintenance time to fix mechanical problems has been spent for the problems 'reduced function' and 'partial damage', while roughly 30% has been spent for the problems 'no function' and 'leakage'.

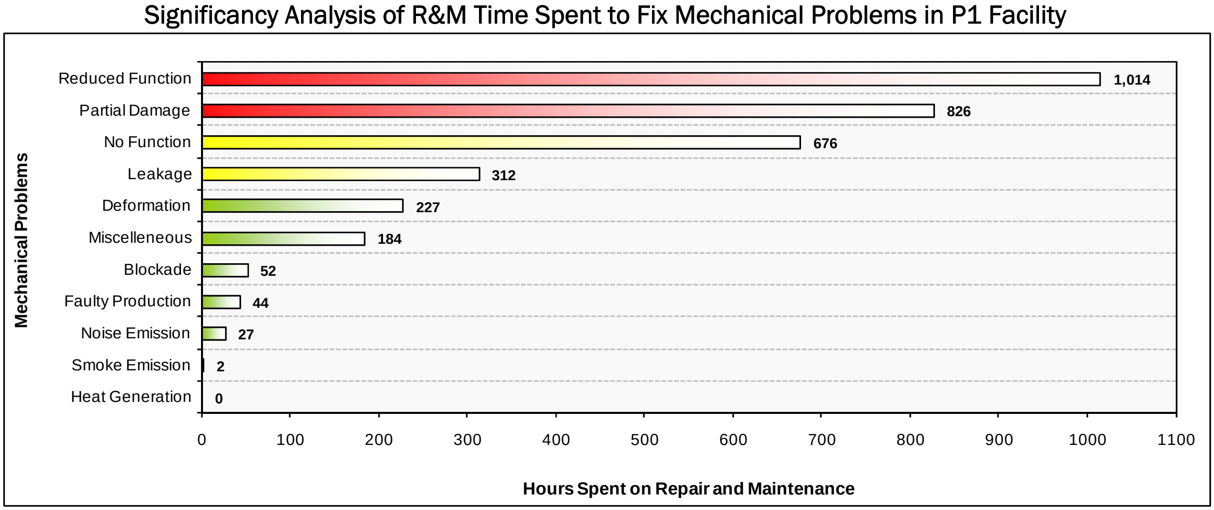
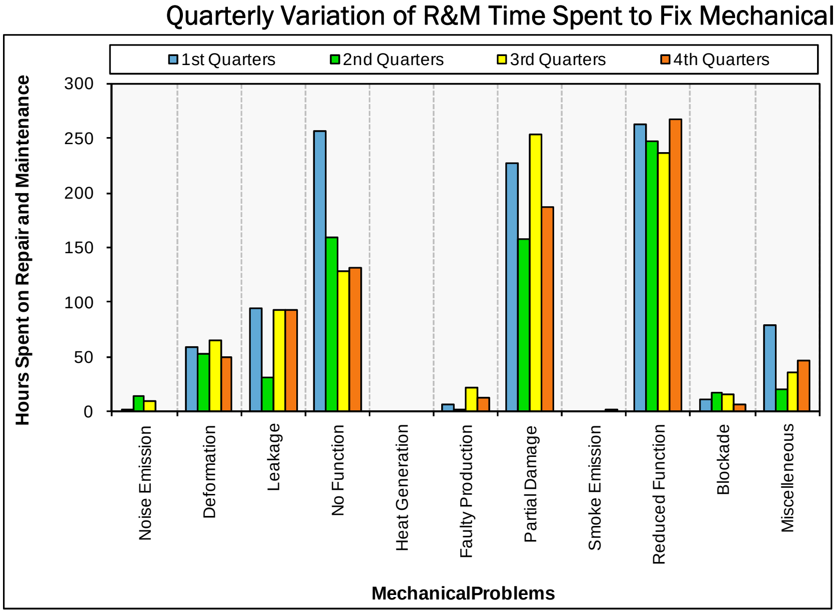


Figure 81 Number of hours spent on repair and maintenance of mechanical problems occurred in the P1 facility from 01.07.05 to 30.06.09

The most and the least R&M time consuming month of the year to fix different mechanical problems can be determined. Such information facilitates maintenance department with an overview of the most workforce consuming mechanical problems and thus helps to decide for which maintenance techniques and technologies it has to invest. For example, the most R&M time consuming month to fix the problem of leakage has been December with associated 12.6 hours on average while the least R&M time consuming month has been June with only 1 R&M hour on average. On the whole, the most and the least R&M time consuming months to fix the occurred mechanical problems have been accordingly March and July with corresponded 99.6 and 53.7 R&M hours on average. Similarly the most and least R&M time consuming quarters to fix the occurred mechanical problems have been the 1st and the 2nd quarters with respective 249.6 and 176.5 R&M hours on average.

The variation of total R&M time spent to fix different mechanical problems in a facility with respect to particular periods of time contains important information. Figure 82 displays the variation of total repair and maintenance time spent to fix different mechanical problems in the P1 facility with respect to the quarter in which they were occurred. For example, partial damages have consumed more R&M time in the 3rd quarters while blockades have devoured more time for their repair in the 2nd quarters. Such a timely variation can be plotted on a monthly basis. Figure 83 represents such a monthly variation and can be used to simply identify the most R&M time consuming months for different mechanical problems in the P1 facility; for instance, the month of August for the mechanical problem 'faulty production'.



As the graph on the left represents, the most R&M time consuming mechanical problems occurred in the P1 facility from 01.07.2005 to 30.06.2009 have been 'reduced function', 'partial damage' and 'no function'. While 'reduced function' has guzzled more R&M time in 4th quarters, 'partial damage' and 'no function' have consumed more R&M time in 3rd and 1st quarters respectively. Besides, while the R&M time consumed was the lowest in 3rd quarters for reduced function, for leakages it was the case in 2nd quarters. Again, a crucial issue is the terms used to categorize the mechanical problems: e.g. while 'leakage' denotes perfectly a problem, 'reduced function' signifies the situation rather than specifying the problem itself.

Figure82 A Number of hours spent on repair and maintenance of mechanical problems in the P1 facility with respect to the quarter of occurrence from 01.07.05 to 30.06.09

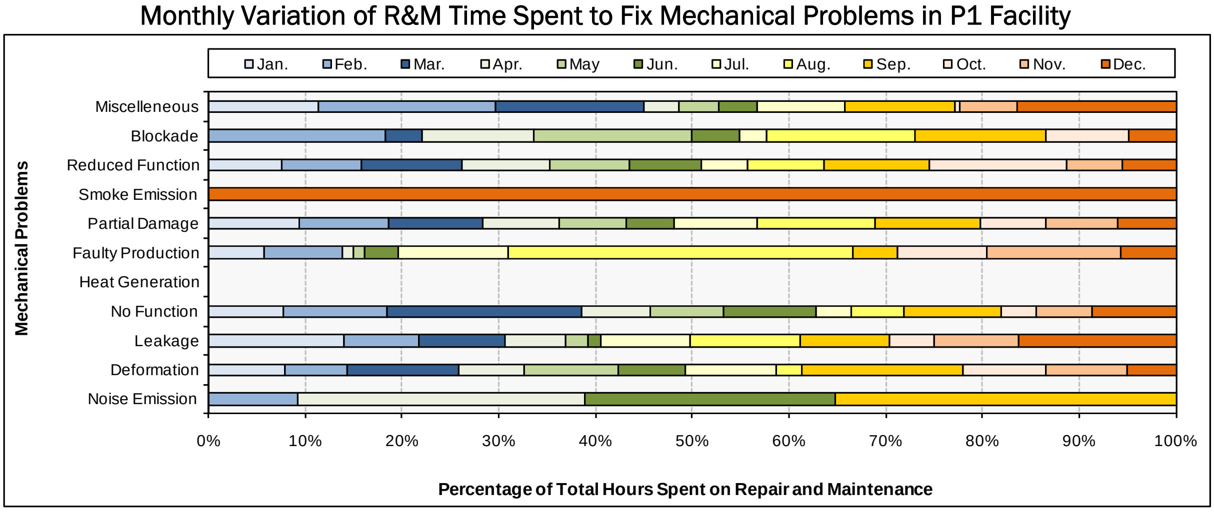


Figure 83 Percentage of total hours spent on repair and maintenance of mechanical problems in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

5.8 Summary and Future Development Potentials

As it has been shown throughout this chapter, the statistical failure analysis utilizes different statistical tools and provides a broad range of information that can be used for a variety of purposes. The resultant information out of the undertaken analyses basically represents the genetic code of a facility or plant in a graphical or tabulated manner. This makes SFA very handy to be used by different people with diverse technical backgrounds:

Table 19 Overview of the statistical failure analyses, their use and products

Statistical Failure Analysis	Provides:	Defines/Indicates:
Time Based Failure Analysis	Time based track and trend of H1 transactions in a facility	All transactions related to major failures
	Time based track and trend of H2 transactions in a facility	All transactions related to minor failures
	Time based track and trend of H3 transactions in a facility	All transactions related to planned maintenance
	Time based track and synopsis of major failures in a facility	Time attribute of major failures/overall performance
	Time based track and synopsis of minor failures in a facility	Time attribute of minor failures/overall performance
Station Based Failure Analysis	Station based synopsis of major failures in a facility	Most failure-critical stations
	Station based synopsis of minor failures in a facility	Most problem-making station
	Station based synopsis of planned maintenance in a facility	Most plannedly maintained station
	Significancy analysis of Stations of a facility	Criticality ranking of different stations
	Station based synopsis of problems in a facility	Annual variation of total problems of each station
	Station based classification/synopsis of nature of problems occurred in a facility	Total number and annual variation of electrical and mechanical problems occurred in each station
	Station based classification of problems occurred in a facility	Total number of damaged machinery and equipment object in each station
	Time based synopsis of problems occurred in different stations	Time attribute of problems occurred in each station
	Station based synopsis of damaged equipment and machinery objects in a facility	Most failure critical machinery objects in stations
Object Based Failure Analysis	Time e based synopsis of damaged equipment and machinery objects in different stations	Time attribute of damaged machinery and equipment object/a quality and maintenance indicator
	Significancy analysis of damaged equipment and machinery objects	Criticality ranking of different equipment and machinery objects
	Identification of the most vitiated stations of a facility by different equipment and machinery objects	Most deteriorated stations by failure of particular equipment and machinery objects
Problem Based Failure Analysis	Time based synopsis of electrical and mechanical problems occurred in a facility	Time attribute of different electrical and mechanical problems
	Significancy analysis of electrical and mechanical problems occurred in a facility	Criticality ranking of different electrical and mechanical problems
	Identification of the most problematic stations according to the nature of occurred problems in a facility	Most deteriorated stations by occurrence of different electrical and mechanical problems
	Identification of the most problematic machinery objects according to nature of occurred problems in a facility	Most deteriorated machinery objects by occurrence of different electrical and mechanical problems
Cause Based Failure Analysis	Time based synopsis of electrical and mechanical problem-causes incurred in a facility	Time attribute of different electrical and mechanical problem-causes
	Significancy analysis of electrical and mechanical problem-causes incurred in a facility	Criticality ranking of different electrical and mechanical problem-causes
	Identification of the most degraded stations according to the nature of incurred problem-causes in a facility	Most deteriorated stations by occurrence of different electrical and mechanical problem-causes
	Identification of the most degraded machinery objects according to nature of incurred problem-causes in a facility	Most deteriorated machinery objects by occurrence of different electrical and mechanical problem-causes
Statistical Problem Cause Analysis	Identification of the most incurred problem-causes and their correlation with different problems	Most frequent causes of particular electrical and mechanical problems
Time Based Maintenance Analysis	Determination and synopsis of total repair and maintenance time spent on different stations	Seasonal/periodic attribute of total R&M time spent on each station
	Significancy analysis of total repair and maintenance time spent on different stations	Cruciality ranking of different stations based on the total R&M time spent on each
	Determination and synopsis of total repair and maintenance time spent on different damaged equipment and machinery objects	Seasonal/periodic attribute of total R&M time spent on each equipment and machinery object
	Significancy analysis of total repair and maintenance time spent on different damaged equipment and machinery objects	Cruciality ranking of different equipment and machinery objects based on the total R&M time spent on each
	Determination and synopsis of total repair and maintenance time spent to fix different occurred problems	Seasonal/periodic attribute of total R&M time spent on each electrical and mechanical problem
	Significancy analysis of total repair and maintenance time spent on different occurred problems	Cruciality ranking of different electrical and mechanical problems based on the total R&M time spent on each

Indeed, the mentioned factors are only direct results of undertaking a statistical failure analysis in a facility. Analyzing and discussing each and every of the resultant graphs and tables in details would itself reveal some precious information that can be used by different departments in a manufacturing or processing plant. In other words, the indirect resultant information of having such an analysis is also so valuable that makes statistical failure analysis a priceless tool with no substitute. If the statistical failure analysis is undertaken for each and every station in a facility the attained results can be exploited to optimize the inventory level and effectively run a spare part management program. Besides, SFA can be also employed to obtain an overview of the undertaken planned maintenance in a facility and to measure its effectiveness and performance. Nevertheless, the author has developed such a SFA as tool to be used within condition based maintenance program in combination with other tools such as a knowledgebase for different condition monitoring techniques and nondestructive tests, and the problem-cause analysis.

As a future development potential, more complicated descriptive statistics and inferential statistics can be used for diagnosis and prognosis of the available data. Inferential statistics uses patterns in the sample data to draw inferences about the population represented, accounting for randomness. These inferences may take the form of: answering yes/no questions about the data (hypothesis testing), estimating numerical characteristics of the data (estimation), describing associations within the data (correlation), modeling relationships within the data (regression), extrapolation, interpolation, and data mining. Besides, other factors can be taken into account to construe certain conclusions. For instance, in the developed statistical failure analysis, based on relative standard deviation, the items (e.g. a station or a machinery object) which have a lower RSD are more appropriate to be maintained via planned maintenance or kept in the inventory as spare parts. This is due to their steady and invariable failure behavior as they have shown relatively similar failure frequencies in particular time periods. However, one may consider and associate other factors such as cost and risk of failures of these items, and make such decision like appropriateness for maintaining by planned maintenance based on multi variable factors instead of a single one.

6 CMT/NDT Knowledgebase for the CBM Toolbox

The reliability of a condition monitoring technique or a nondestructive test is an essential issue. But a comparison of different methods is only significant if it is referring to the same task. Each CMT/NDT has its own set of advantages and disadvantages, and therefore, some are better suited than others for a particular application. Indeed, the effectiveness of any particular CMT/NDT depends upon the skill, experience, and training of the person(s) performing the inspection and testing process. Each process is limited in its usefulness by its adaptability to the particular component to be analyzed. The type of component and nature of possible failures generally specify the particular test and procedure to be used. The CMT/NDT knowledgebase contains 14 major condition monitoring techniques and nondestructive tests used for purpose of condition based maintenance in different manufacturing and processing industries. The tests themselves may be consisted of a variety of methods. On the whole, the knowledgebase includes expert knowledge about more than 45 different methods and techniques which has been structured and categorized in a way to make it as useful as possible, and thus turn it to intelligence. Table 20 provides an overview of the CMTs/NDTs included in the knowledgebase.

Table 20 Condition monitoring techniques and nondestructive tests included in the CMT/NDT knowledgebase

1. **Acoustic Emission Testing** (AT)
2. **Electrical Inspection** (EI)
    - Dynamic Inspection
    - Static Inspection
3. **Electromagnetic Testing** (ET)
    - Eddy Current testing
    - Magnetic Flux Leakage Testing
    - Remote Field Testing
4. **Laser Inspection** (LI)
    - Laser Alignment
    - Laser Holography
    - Laser Profilometry
    - Laser Shearography
    - Laser Vibrometry
5. **Leak Testing** (LT)
    - Bubble Emission Leak Testing
    - Chemical Reaction Leak Testing
    - Gas detection Leak Testing
    - Halogen Diode Leak testing
    - Hydrostatic Leak Testing
    - Pressure Change Leak Testing
    - Radioisotope Leak Testing
    - Tracer Gas Leak Testing
    - Vacuum Flow Leak Testing
6. **Magnetic Particle Testing** (MT)
    - Dry Particle Inspection
    - Wet Suspension Inspection
    - Magnetic Rubber Inspection
7. **Penetrant Testing** (PT)
    - Fluorescent – Type-I
    - Visible – Type-II
8. **Radiographic Testing** (RT)
    - Film Radiography
    - Digital radiography
    - Computed Radiography
    - Computed Tomography
    - Neutron Radiography
    - Neutron Radioscopy
    - Neutron Tomography
9. **Stress Wave Analysis** (SA)
10. **Thermal Inspection** (TI)
    - Passive Thermography
    - Active Thermography
11. **Tribological Testing** (TT)
    - Contamination Analysis
    - Oil Analysis
    - Wear Analysis
12. **Ultrasonic Testing** (UT)
    - Lamb Waves Inspection
    - Pulse-Echo Inspection
    - Tip-Diffraction Inspection
13. **Vibration Analysis** (VI)
    - Free-vibration analysis
    - Forced-vibration analysis
14. **Visual/Optical Inspection** (VI)
    - Eye-Mirror-Flashlight Inspection
    - Borescopic Inspection

6.1 Knowledge Acquisition

To create a knowledgebase about various condition monitoring techniques and nondestructive tests two types of information must be gathered and transformed into useful knowledge: Information representing the facts about the tests that can be deduced from various scientific and technical literatures; and experience representing the knowledge collected over a period of time from experts or empirical tests [349]. Useful knowledge refers to the abstraction of information structured in a way such that inferences about various tests can be drawn in a consistent manner. It should be possible to structure, organize, and store knowledge for easy and timely access, add more knowledge as time passes by, extend the current knowledgebase to include more types of knowledge, and clarify the differences in a transparent and intuitive manner to generate intelligence.

For development of the CMT/NDT knowledgebase, the author gathered information and experience which then transformed into useful knowledge and saved in a centralized repository allowing the users to easily retrieve and utilize its expert contents. Although the repository is not yet in the form of a smart, algorithmic software, it is definitely a knowledgebase since it is not a static collection of information, but a dynamic resource that can be or indeed required to be continuously updated and improved based on the recent technological and scientific developments and the self-generated knowledge by the toolbox. Sections 6.2 to 6.15 describe tests and methods included in the CMT/NDT knowledgebase in details.

6.2 Acoustic Emission Testing

Acoustic emission testing (AT) relies on the use of passive transducers and receptive techniques to listen for mechanical disturbances caused by various degradation processes in industrial machinery and equipment. In principle the AT method is very simple, but in practice it can be difficult to separate the vibration signals caused by normal in-service processes from those associated with degradation and damage. In spite of this, AT is frequently used in particular applications, such as the monitoring of stressed structures, pressure vessels, fluid capsules, and corrosion, wear and leak detection.

6.2.1 Conception

Acoustic emission pertains to nondestructive testing methods and is used to locate and characterize developing cracks and defects in different materials. In non-destructive testing of machinery structures, acoustic emission is a well-accepted method and has been used for some time now in various industrial applications [419]. Though, AT of complex machinery is a challenging and difficult problem. Such structures involve bolts, fasteners and plates with possible relative motion to one another. The more complex is the geometry of the structure, there exist more multiple mode conversions of acoustic emission source signals that compound the difficulty of relating source event to detected signal [339].

Simply, acoustic emission is defined as a transient elastic wave generated as a result of material deformation or discontinuity. This stress wave propagates through the material as a result of sudden energy release during the deformation process. The released energy carries characteristics of the source mechanism although it is also affected by the material through which it travels. Sensors mounted on the surface of material detect this pulse of energy [539], [591]. Acoustic activity may be observed both in highly elastic as well as brittle materials. The classical sources of acoustic emissions are defect-related deformational processes such as crack nucleation or growth, dislocation movement, irregular friction and plastic deformation [453].

Generally, any discontinuity (e.g. a crack) generation and growth in materials is accompanied by an emission of high frequency sounds in various directions. By placing several sensors on the surface of the material, monitoring the time of arrival of these signals to the sensors, observing the frequency of the emission and the amplitude of the event, the nature of the discontinuity in the material can be quantified [295]. Nevertheless, understanding an acoustic signal requires the knowledge of certain terminologies of burst signal parameters central to analyze and interpret these signals. Some of these parameters are listed below [261], [453]:

- *Arrival Time:* It is the absolute time when a burst signal first crosses the detection threshold. Corrections may be required for the deviations due to sensory instrument death time or electronic delays.

- *Duration:* It is the interval between the first and the last time the detection threshold was exceeded by a burst signal. This parameter measures the source event magnitude and it is specifically useful for noise filtering.

- *Peak:* Maximum absolute amplitude within the duration of the burst signal. The amplitude is directly related to the magnitude of the source event.

- *Rise Time:* It is the time interval between the first threshold crossing and the maximum peak amplitude of the burst signal. Analysis of this parameter is often useful in problems involving time-dependent processes such as dynamic loading or vibration of structures.

- *Counts:* It is the number of detected burst signals crosses the detection threshold.

- *MARSE:* Measured Area of the Rectified Signal Envelope is a measurement of the area under the envelope of the rectified linear voltage time signal from the sensor. In signal analysis, this parameter is usually preferred over counts as it is sensitive to both amplitude and duration, and less sensitive to operating frequency and threshold setting.

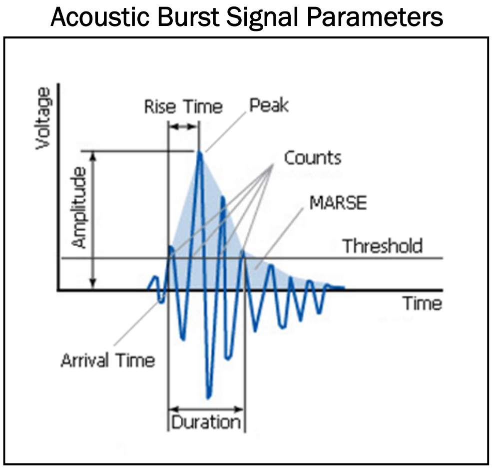


Figure 84 A graph showing different signal parameters on an acoustic emission burst. The threshold is an amplitude measurement used for calibration of instrumentation

It is worth to take into account that acoustic emission signals are not only produced by defects or discontinuities but can also originate from disturbances such as peaks of the background noise, which sometimes exceed the threshold; hence, it is vital to determine those characteristics which allow distinguishing the wanted from unwanted signals. The peak amplitude is one of the most important signal parameters in this sense.

Burst signals which represent discontinuities usually have medium to high amplitudes and have durations of some 10^{-5} seconds, depending on the specimen's structural design and material properties. More often than not, signals with less than 3 threshold crossings and duration less than 10^{-6} seconds are considered as the unwanted ones. Most of the signals with low amplitudes and long duration are friction noise and, in addition, very short signals may indicate electrical noise peak, especially, if they arrive at all channels at the same time [637].

The accuracy of data collected using the acquisition equipment is affected by different factors. Attenuation or loss signal amplitude due to material damping and also the geometry of the material may be considered as the main influential ones [591]. Wave velocity, specimen's geometry and material properties are all factors that vary the amount of acoustic activity generated [539]. Even the kind of stress and rate of loading applied to the material generates a different acoustic emission signature. High acoustic emission may be directly associated with damage of material, crack propagation, low-temperature deformation and brittle fracture [364].

On the whole, AT differs from most other nondestructive testing methods in two major respects. First, the signal has its origin in the material itself and is not injected into the object from an external source. Second, acoustic emission detects movement in addition to existing geometric discontinuities or breaks, while most other methods only do the second task [409].

6.2.2 Tools and Techniques

Acoustic emission monitoring is realized using a group of instrument, each of which has a specific role to play and is required for an appropriate and accurate process. In this group, sensors are key means to detect the mechanical acoustic waves from within a structure and convert them into electrical acoustic emission signals. In practice, piezoelectric resonant sensors are usually used for AT. Sensors, however, are affixed to the surface of specimen using various couplants. Couplants (e.g. oil, glue and high vacuum grease) are basically used to facilitate an easy and complete conduction of acoustic waves. Besides, pre-amplifiers are employed to provide gain, boosting signals to a less vulnerable level and to effectively filter the noise from areas outside the sensor operating range. In addition, a data acquisition system, which consisted of computers and proper software, is required to attain and store the received signals. The new generation of such systems also facilitates extensive post-processing possibilities and they are also well adapted for continuous monitoring of machinery using wireless technology and web-based remote monitoring [453].

Within this framework, acoustic emissions may be collected and analyzed on a parametric or waveform basis. The new data acquisition systems are able to collect data in both forms. The usual parametric data recorded are the burst signals amplitude, counts, duration and so on. On the other hand, acoustic emission sources are usually identified by calculating the difference in time taken for the wave to arrive at different sensors or based on the waveform. The velocity of the waves in the specimen is determined using pulse velocity method. The most notable advantage of this technique is that it provides quantitative information regarding discontinuity behavior and propagation rate. However, such a technique is considered as a very sophisticated method that requires highly qualified personnel. For instance, the crack location problem is typically solved by various triangulation techniques, which are based on the analysis of ultrasonic ray trajectories [117], [207], [617], [683]. Solving and programming of related equation is rather cumbersome and cannot be simply performed if the structure of the tested specimen is geometrically complicated [233].

6.2.3 Use and Applicability

Acoustic testing, an increasingly popular NDT technique, has been used to identify a variety of discontinuities like cracks, wear and deformation in different materials. Its different techniques and equipment have emerged for specialized applications in stationary and rotating machinery such as crack initiation and growth, corrosion control, fatigue monitoring [364]. Of these, fatigue monitoring has been more developed to the point of producing quantitative data about specific defects [289]. Acoustic emission monitoring is also effective as a screening tool, especially when verified with a complementary NDT techniques, usually ultrasonic testing. Acoustic emission has proven successful in monitoring and testing the following structures and machinery: Tanks, vessels, bullets, spherical shaped structures, reactors, adsorbers, drums, pipes, tubes, fluid lines and fiberglass booms [1]. Acoustic emission testing is also used for some specific purposes like bearing defect diagnosis gear fault detection and leak detection and localization.

AT was initially developed for nondestructive inspection of static structures, yet, over the years its application has been extended to condition monitoring of rotating machines and more specifically, bearings. The formation of subsurface cracks due to the contact stress induced by the rolling action of the bearing elements in contact with the inner and outer races, and, the rubbing between damaged mating surfaces within the bearing will generate acoustic emission activity. In 1980s, some scientists researched acoustic emission activity from bearing defects and found different signal parameters associated with bearing defects noting that the signals detected in the specific frequency range represented bearing defects rather than other defects such as imbalance, misalignment, looseness and shaft bending. Yoshioka and Fujiwara [676] and Hawman and Galinaitis [257] have proven that the acoustic emission parameters identify bearing defects before they appear in the vibration acceleration range. The research in this field has been followed by other scholars like Tandon and Nakra [597], Mba et al. [414], [415], Choundhury and Tandon [129], and Jamaludin et al. [300].

Coming to the gear fault detection, although whilst vibration analysis is well established and the application of AT sounds infancy but the use of acoustic emission testing has become the focus of practitioners in recent years. The focal downside with the application of the AT is the attenuation of the acoustic emission signal and as such the sensor has to be placed close to the source. Although, it is often practical to place the sensor on the non-rotating member of the machine, such as the gearbox casing, but as a consequent, the acoustic emission signal originating from the defective component suffer severe attenuation before reaching the sensor. Despite, there have been extensive research efforts by many scholars and with the advancement of technology; AT has started to be used practically for gear fault detection in industry [545], [564], [598], [599], [621].

Another application of acoustic emission testing is in leak detection and localization. AT can be used in this respect to detect the leakage from insulated pipes, tubes and lines of machinery or equipment (as machinery condition based maintenance) or even the ones located within the building structure of a plant (as a plant’s facility maintenance and management). For this to be realized, acoustic emission sensors receive and transfer the signals to a signal acquisition system in which they are digitalized and then fed into a signal and data processing system. Afterwards, using a data base the signals are classified and based on that the damage type which can be a leakage is identified.

Application Process of AT in Leak Detection, Localization and Analysis

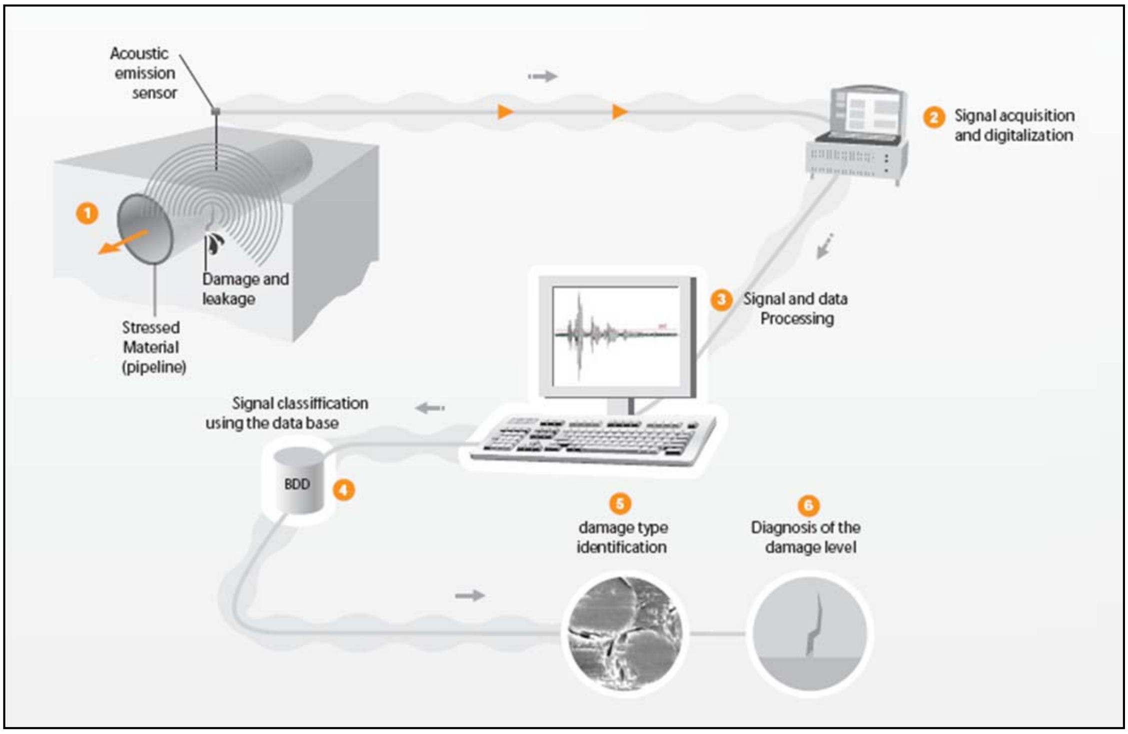


Figure 85 A picture showing different process steps of leak detection, localization and analysis, using acoustic emission testing and related tools and techniques [WS6].

Among all, one of the most powerful methods of using acoustic emissions to monitor materials is through change detection. To illustrate, acoustic emissions from metals arise when an increase in local strain (i.e. around a defect) causes deformation (i.e. growth of the plastic zone or crack growth). This may be due to fatigue, corrosion or other chemical attack, a stress increase or temperature change, or some combination of these factors. Suitably placed sensors and monitoring equipment can detect the small displacements (i.e. stress waves) created by this process. Within the change detection framework, acoustic emission rates are recorded throughout a conventional cycle of use of the material, and these are compared from one cycle to the next without trying to understand the underlying causes of the temporal pattern. It is the changes in temporal pattern of acoustic emissions as the material ages over many (e.g. hundreds or thousands) of cycles that is important, and extraneous noise due to benign motions is therefore not a concern. Small transducers can be located near highly stressed points within a structure or piece of equipment, and the resulting frequency-dependent amplitudes of acoustic emissions can be readily monitored using data loggers or minicomputers. The amplitude and frequency contents of the emissions can be compared from cycle to cycle. Moreover, most sophisticated means of data analysis, which can reveal information about stress distributions, are beginning to be used [1].

6.2.4 Limitations and Pros

Acoustic emission testing is gaining ground as a non-destructive technique for machinery condition monitoring. There are vast opportunities for development of AT techniques on various forms of machinery and equipment. Nevertheless, AT has a number of limitations and advantages which have to be always kept in mind. For example, early research showed that acoustic emission was proportional to stress intensity (i.e. from AT's perspective a shallow but sharp crack is equivalent to a deep, blunt crack). Despite the fact that AT arises from defect propagation or deformation processes, it is not a very practical on-stream monitoring technique for several reasons [473]:

- *Continuous background noise:* High levels of background noise due to fluid or gas flow may completely obscure the majority of acoustic emission signals.

- *Impulsive background noise:* Noise of this type is produced by a wide range of mechanisms such as bubbling, splashing, particle impact, scale spalling, and fretting of bolted parts. These noises may produce acoustic signals very similar to those from cracking.

- *Analysis techniques:* With some notable exceptions, analysis of on-stream monitoring data is difficult, especially when operating parameters such as temperature and pressure remain constant. While it is often possible to determine that some degradation is occurring, arriving at some measure of the significance or progress of the damage is not easily possible.

On the other hand, its unique ability to passively record events at their moment of occurrence is definitely the main reason for this technique to come in to the forefront of structural monitoring. This advantageous quality permits monitoring during loading. The technique can also be characterized as dynamic and volumetric since it is well adapted for remote monitoring of active defects on varied machinery structures. Another major benefit of AT is that it allows the whole volume of the structure to be inspected nonintrusively in a single operation [134]. Classically, overall acoustic emission inspection is used to identify areas with structural problems, and other NDT methods are then used to identify more precisely the nature of the acoustic emission sources. Depending on the case, acceptance or rejection of results can be based on AT alone, other NDT methods alone, or all-together. The relatively high cost of equipment and specialized training required to operate and analyze the data obtained from each test may have limited AT's use in the past, but in more recent times, it appears that more technical personnel are prepared to use this technique as part of their condition based maintenance programs to reduce their operating costs, by eliminating unnecessary and sometimes intrusive inspections [409].

Since AT is usually compared with vibration analysis methods by many technicians and engineers in industry it is important to highlight their merits and demerits over each other. Beginning with AT's merits, it has to be considered that: Acoustic emission waves propagate in all directions from the source whereas vibration is largely unidirectional, hence, acoustic emission waves are usually easier to be found; AT sensors are less sensitive to normal running and process activities of machinery at higher frequencies which facilitates a clearer and more better identification of presence of a fault mechanism; AT is much more effective on slow rolling element, plain and linear bearings, where traditional vibration techniques are ineffective because of low signal to noise ratio at very low frequencies; in AT in contrast with vibration analysis, machinery speed variations have little or no effect on the achievable results, plus, signal propagation from the source to the sensor is unaffected by structural resonances. Coming to AT's demerits, one may take into account that: misalignment, imbalance and insecurity are not readily detectable by AT; the test's ability to detect discontinuities can be masked by cavitation; and, AT usually offers no detailed information to enable diagnosis of the fault type. However, it should not be overlooked that diagnosis of fault type is seldom required for inexpensive machinery components, and therefore, AT is more appropriate for condition monitoring of these [411], [274], [275].

Table 21 Synopsis of acoustic emission testing

Pros	▪ Ability of defect localization ▪ Possibility of real-time monitoring ▪ Very sensitive to small discontinuities ▪ Chance of controlling of inaccessible zone ▪ Portable equipment available for some applications ▪ Machinery structural resonances have no effect on test results ▪ Clearer indication of presence of flaws in comparison with other wave-based tests ▪ Speed variation of moving machinery elements has nearly no effect on test results ▪ Providence of quantitative information regarding crack behavior and propagation rate ▪ Higher chance of flaw detection due to multidirectional propagation of acoustic emissions	
Limitations	▪ Skill and training required ▪ Sensitive to background noise ▪ Possibility of being masked by cavitation ▪ Complicated in analysis of on-stream monitoring data ▪ Very poor in detection of misalignment, imbalance and insecurity ▪ Incapable of providing detailed information about the discontinuity type	
Equipment	▪ Sensors, couplant and a data acquisition system (i.e. computer and software) ▪ Automated scanning and single frequency or multi frequency equipment are also available	
Discontinuity types	▪ Crack ▪ Pitting ▪ Fatigue ▪ Porosity ▪ Fracture ▪ Disbond ▪ Inclusion	▪ Cavitation ▪ Impact wear ▪ Delamination ▪ Surface-breaking ▪ Coating disbonding ▪ Nonsurface-breaking
Discontinuities size	▪ Very small but evolutionary discontinuities can be identified	
Relative inspection cost	▪ Equipment costs vary from a modest to a relatively high amount	

6.3 Electrical Inspection

Having profitability margins become narrower, reducing operating and maintenance cost of industrial machinery which run by electrical motors or the motors themselves is of supreme importance. With appropriate electrical inspection (EI) of motors, it is possible to lower the operation and maintenance cost per every watt or horsepower for a wide range of motor-driven machinery and in various manufacturing and processing industry. Periodical and continuous electrical inspections have proven to increase motors' and motor-driven mechanical systems' lifespan, reduce downtime, and in most cases reduce the expense of performing reactive and planned maintenance activities [82].

6.3.1 Conception

As electrical inspection is mostly about examining motors it is beneficial to have an overview of these devices. An electric motor is a machine which is used to convert electrical energy to mechanical energy. The major physical principles behind the operation of an electric motor are known as Ampere's law and Faraday's law. Ampere's law avers that an electrical conductor in a magnetic field endures a force if any current flowing through the conductor has a component at right angles to that field. Reversal of either the current or the magnetic field generates a force in the opposite direction. Faraday's law avows that if a conductor is budges through a magnetic field, then any component of motion perpendicular to that field creates a potential difference between the ends of the conductor [168].

Any electric motor is mainly comprised of two essential components: stator, which consists of magnetic materials and electrical conductors to generate magnetic fields of a desired shape; and, rotor (or armature in DC motors), which is also made from magnetic and electrical conductors to generate shaped magnetic fields that interact with the fields generated by the stator. The rotor is the moving part of the motor, having a rotating shaft to connect to the machine to be run by the motor and some means of maintaining an electrical contact between the rotor and the motor housing (e.g. carbon brushes). The electrical current supplied to the motor is used to create magnetic fields in both the stator and rotor. These magnetic fields act against each other and generate a torque that rotates the rotor [51].

In general, electrical motors are categorized into three types: direct current (DC), alternating current (AC), and universal motors. DC motors run through the help of direct current. They provide quick power bursts of up to five times the rated torque. Their speed can be brought down to zero smoothly and immediately raised in the opposite rotational direction without any power interruption. DC motors have an electromagnet with two poles, which serve as a rotating armature. A commutator or a rotary switch is used to reverse the current direction twice in each cycle. This causes the poles of the electromagnet to push and pull against the external permanent magnets. When the poles of the armature pass through the poles of the permanent magnet, the commutator reverses the polarity of the armature. The inertia maintains the current direction at the instance when polarity is switched. Basically, there are four different types of DC motors which are used in different industrial applications [454], [462], [486]:

- **Series Wound DC Motor:** This motor has the armature and field windings connected in a series circuit. The starting torque developed can be as high as 5 times the full load rating. The series wound motor is able to deliver this high starting torque due to the fact that its field is operated below saturation point. It is central to consider that when the load on the motor is dropped off the current flowing in the armature and field circuits is reduced causing a reduction in their flux densities and consequently a decrease in hold-back electromotive force. Hence, when the load is reduced, speed increases. If there is no load, the speed of the motor would increase to infinity until it destroys itself.

- **Shunt Wound DC Motor:** This motor has the armature and field windings connected in parallel or it may have separate field and armature supplies. With constant armature voltage and field winding excitation, this type of motor offers relatively flat speed/torque characteristics. The starting torque developed can be up to three times of the full load torque rating for a short period of time. Its speed regulation (i.e. speed fluctuation due to load) is in an acceptable range of 5% to 10% of maximum speed, when operated from a DC drive. This type of DC motor is probably the most widely used DC motor in industrial applications. Typical applications for this motor would be printing presses, plastic extruders, conveyors, and practically any other application where DC motors are used. Because of the need for two power supplies, this type of motor is a prime candidate for a DC drive.

- **Compound Wound DC Motor:** This type of DC motors is basically a combination of shunt wound and series wound configurations. It offers high starting torque of a series wound motor as well as constant speed regulation or speed stability under a given load. This motor is used whenever speed regulation cannot be obtained from either a series or shunt wound motor. The torque and speed characteristics are the result of placing a portion of the field winding circuit in series with the armature circuit. The commutation windings also have a few turns, but have the duty of neutralizing armature reaction. When a load is applied, the increasing current through the series winding increases the field flux, thus increasing the torque output of the motor. As a result, this increase in field flux will yield a greater reduction in speed, for a given load change, than a shunt motor.

- **Permanent Magnet DC Motor:** This motor is built with a standard armature and brushes, but has permanent magnets in place of the shunt field winding. The speed characteristic is close to that of a shunt wound DC motor. When adding the cost of a DC motor and control system, this type of motor is less expensive to operate, since there is no need for a shunt field winding exciter supply. Permanent magnet DC motors are generally used where response time is a factor. Although this motor has a very good starting torque capability, its speed regulation is slightly less than that of a compound wound motor. The overall torque output makes it a prime candidate for low torque applications. It can, however, lose their magnetism with age and as a result produce less than rated torque. Some permanent magnet motors have windings built into the field magnets for remagnetizing.

A Typical Industrial Motor

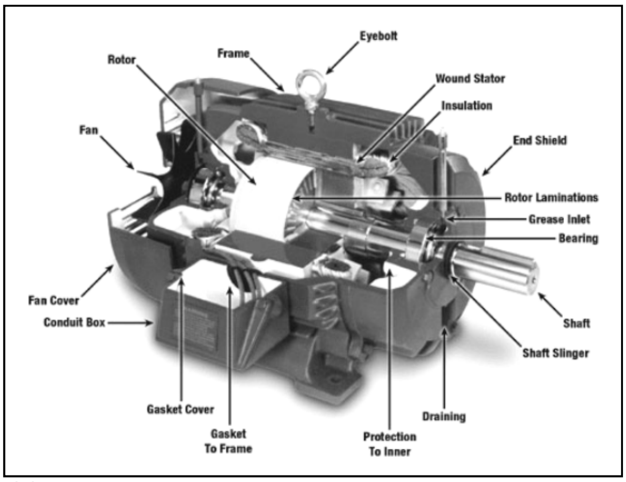


Figure 86 Different components of a typical industrial motor [WS41]

Alternating current motors or AC motors allow long range distribution of alternating current. An AC motor has two main parts, a fixed external stator and an internal rotor. The stator has coils through which AC current flows and generates rotating magnetic field. The rotor is attached to the output shaft and gets a torque by the rotating magnetic field. The AC Motors meet their applications in two forms based on their power supply. The single phase motors are generally found their use in low-power required appliances like ceiling fans, mixer grinders, and portable power tools. The polyphase motors are generally employed in manufacturing and processing industry and found their application in high-power required mechanical systems such as power drives for compressors, hydraulic and irrigation pumps, and air conditioning compressors. Mainly, there are three different types of AC motors used in [232], [283]:

- **Synchronous AC Motor:** This motor has fixed stator windings electrically connected to the AC supply with a separate source of excitation connected to a field winding on the rotating shaft. Magnetic flux links the rotor and stator windings causing the motor to operate at synchronous speed. When the motor reaches its synchronous speed, it is locked in step with the stator by application of a field excitation. When the synchronous motor is operating at synchronous speed, it is possible to alter the power factor by varying the excitation supplied to the motor field. In fact, this is the way synchronous motors are differentiated from induction motors as they are not self-starting. They have to be brought up to synchronous speed. Once they are locked then the rotor will continuously rotate. An important advantage of a synchronous motor is that its power factor can be controlled by adjusting the excitation of the rotating DC field. Unlike AC induction motors which run at a lagging power factor, a synchronous motor can run at unity or even at a leading power factor.

Synchronous motors can be classified as brush excitation or brushless excitation. Brush excitation consists of cast-brass brush holders mounted on insulated steel rods and supported from the bearing pedestal. The number of brushes for a particular size and rating depends on the field current. Sufficient brushes are supplied to limit the current density to a low value. The output of a separate DC exciter is applied to the slip rings of the rotor. A brushless excitation system utilizes an integral exciter and rotating rectifier assembly that eliminates the need for brushes and slip rings. In general, synchronous motor efficiencies are higher than those of induction motors. A synchronous motor's speed/torque characteristics are ideally suited for direct drive of large power, low rpm loads such as reciprocating compressors. Their precise speed regulation makes them an ideal choice to be used for chippers, crushers, pumps, and compressor drives.

Components of a Synchronous Motor

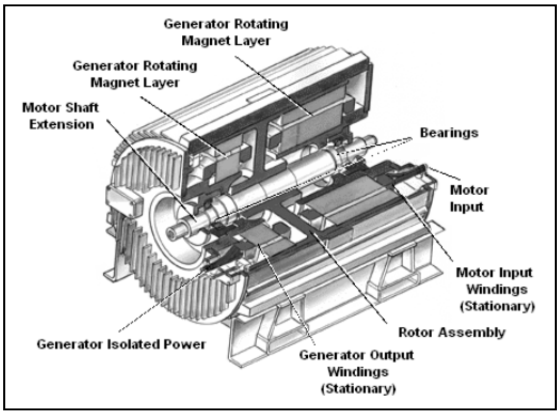


Figure 87 Schematic of different components of a synchronous AC motor [WS60]

- **Induction AC Motor:** An induction AC motor consists of two main parts: a wound stator and a rotor assembly. No voltage is applied to the rotor, but it is applied to the stator winding. When the current flows in the stator winding, a current is induced in the rotor by transformer action. The resulting rotor magnetic field interacts with the stator magnetic field, causing torque to exert on the rotor. The rotor is made up of laminated cylindrical iron cores with slots for receiving the conductors. In early designs, the conductors were copper bars with ends welded to copper rings known as end rings. The modern designs have cast-aluminum conductors and short-circuiting end rings. The rotor turns when the moving magnetic field induces a current in the shorted conductors.

  Induction motors are probably the most common type of AC motor, appearing in wide range of industries and for various applications from running the industrial fans and pumps to lifting the cable elevators. It is also quite common to find AC motors in applications such as compressors, machine tools, conveyors, mixers, crushers, and extruders. The induction AC motor has been widely accepted in many demanding industrial applications, compared with the DC motor as it requires less maintenance. These motors are very flexible to use and match the load demand different industrial machinery. In addition, they provide lots of torque, start easily, and are inexpensive. With its efficient operation and energy savings characteristics, in comparison with various DC motors, the industrial use of AC induction motor will increase even more throughout the next several decades.

Components of an Induction Motor

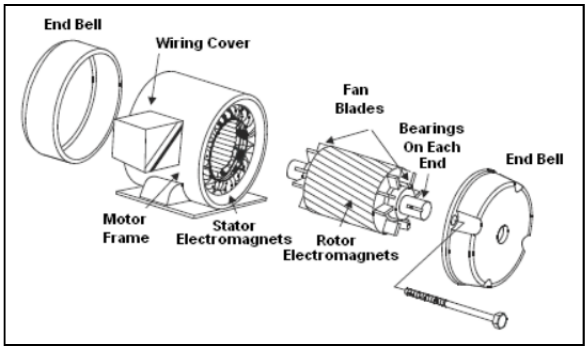


Figure 88 Schematic of different components of an induction AC motor [WS45]

- **Wound Rotor AC Motor:** This motor uses induction to create magnetism too; however, due to its different design and incorporated technique, it is categorized separately. This motor has a wire wound rotor from which three leads are brought out to the slip rings. A wound rotor motor is generally started with a secondary resistance in the rotor circuit. This resistance is sequentially reduced to permit the motor to come up to speed. Thus, the motor can develop substantial torque while limiting locked rotor current. The secondary resistance can be designed for continuous service to dissipate heat produced by continuous operation at reduced speed, frequent acceleration, or acceleration with a large inertia load. It is also possible to vary the rotor resistance by introducing different resistances in the rotor circuit through the slip rings. This is how the motor's speed and starting torque can be kept variable. External resistance gives the motor a characteristic that results in a large drop in rpm for a fairly small change in load; however, its efficiency is not very high.

As the last category, universal motors can run on either DC or AC electric power. Note that a true DC motor cannot stand AC power because its rotational direction will reverse with every half cycle of the power line and it will simply vibrate in place. Similarly, a true AC motor cannot bear DC power as in such motors it is the power line's reversing current that keeps the rotor moving. However, if the permanent magnets of a DC motor are replaced with electromagnets and connected in the same circuit as the commutator and rotor, a universal motor can be made. When DC power is provided to a universal motor, the stationary electromagnets behave as if they were permanent magnets and the universal motor operate just like a DC motor. The only difference is that the universal motor does not reverse directions as the current passes through it. On the other hand, since the universal motor always turns in the same direction, regardless of the direction of current which flows through it, it works just fine with AC electric power. Universal motors are commonly used in appliances like drills, mixers, blenders and vacuum cleaners, and have very limited applications in high-power industrial machinery.

Having different types of electrical motors reviewed and described, the topic of electrical inspection can be opened. However, it is necessary to explain two frequently used terminologies: motor torque and power. The motor torque refers to how much force the motor shaft exerts as it rotates. Torque is dependent on the strength of the magnetic fields in the motor; a stronger magnetic field exerts a stronger pull on the rotor, creating more torque. The force of the magnetic field, and thus torque, is determined by the amount of voltage or current and frequency supplied to the motor. The power of a motor refers to how much work the motor can do, or how much torque it can deliver over time. There are a very wide range of EI methods for condition monitoring of motors and diagnosing some connected mechanical assemblies to them [610]. These methods can be categorized into two major groups:

1. Dynamic Inspection: This method, which is also referred to as on-line testing, is carried out by monitoring the voltage applied and current supplied to the motor at the motor control cabinet (MCC) or connection box. Basically, dynamic inspection is performed at the motor's MCC, at the load side of a variable frequency drive or at an installed port, which allows for on-line testing without opening the control cabinet. Data is collected through a set of current transformers and corresponding voltage probes. The data collected, processed and analyzed provides the technician with an overall view of the operational conditions to which the motor is subjected on a daily basis and of the motor's responses to these conditions. The measured values are then analyzed by utilizing sophisticated algorithms to determine a number of key parameters including power quality (e.g. voltage and power level or imbalance), machine performance (e.g. effective service factor or efficiency), current (e.g. over current), spectrum which designates rotor bar condition, torque and phase relationships [209], [611].

2. Static Inspection: This method, which is also known as off-line testing, incorporates various tests as a series of progressively more rigorous checks, accepting the idea that if a test fails, troubleshooting and repair should begin at that time. Static inspection examines the integrity of the insulation and finds issues related to the stator windings. A complete static inspection includes a wide range of offline tests such as resistance, capacitance and inductance tests, dielectric absorption and polarization index tests, rotor influence check, and step voltage test. To perform these tests, it is required to stop the motor but they can be performed both in the field and in the motor repair shop. Field testing is usually performed at the motor control cabinet, which also allows testing of the cables supplying the motor. It is necessary to highlight that cable problems can cause unplanned shut-downs resulting in expensive repairs, loss of production and may result in motor failures. Therefore, testing cables at the same test standards as the motor is tested is very important [209], [611].

6.3.2 Tools and Techniques

Motor-driven machinery provide core capabilities essential to various manufacturing and processing industries and to safety of equipment and operators. Generally, motors are quite reliable when properly maintained and one should expect many years of satisfactory service and continual operation. However, motors are almost always subjected to a variety of issues that cause premature failure. Thermal aging, mechanical issues and environmental hazards all contribute to the deterioration of motors. For instance, as Thomas claims, years of testing and numerous studies indicates that for every 10°C increase in temperature, the motor's winding life is decreased in half [611].

Essentially, there are seven fault zones based on which motors' problems and the techniques used to identify those problems are categorized. During any motor troubleshooting effort, each of these fault zones must be scrutinized not to miss any existing or potential problem. Each of fault zones requires independent analysis because any fault in any one of these zones will likely blight efficiency and output. Indeed, effective inspection of each fault zone facilitates maintenance personnel with determining the necessary repairs or replacements which maximize motor's efficiency and lifespan. These seven fault zones include [66], [67], [68], [562]:

- **Power Quality:** This is a hypothetical fault zone in which the concerned issue is the condition of voltage and current from the power source entered into the power circuit. A current distress about power quality is the possibility of distortion of voltage and current levels from variable frequency drives and other nonlinear loads. Voltage and current harmonic distortion, voltage spikes, voltage unbalance, and power factor instability are a few of various concerns when regarding to power quality. These distortions give rise to excessive harmonics on distribution system that can result in over-heating of insulation systems, hence, motor's malfunction or shorter lifespan.

- **Power Circuit:** This is a physical zone including all connections from the transformer to the motor. In other words, it refers to the system of conductors and connections from the point at which the testing starts to the connections at the motor which incorporates circuit breakers, fuses, contactors, overloads, disconnects, and lug connections. Malfunctioning or substandard power circuit conditions result in reduced power output rate which consequently bring about overheating and insulation damage. For example, high resistance connections in power circuit cause unbalanced terminal voltages, the consequences of which are: over-heating of the insulation and components adjacent to the connection, torque loss, lower efficiency, and drawing more current to carry out a standard task.

- **Insulation:** The insulation zone takes in all ground wall insulation on all conductors from the switchgear through and including the motor such as the insulation between the windings and ground. The factors that shorten the insulation life include high temperature, age, moisture, and dirt contamination. It is central to highlight that this fault zone is heavily influenced by problems in other zones like power circuit. For instance, if a high resistance connection exists upstream of the motor developing more than 5% voltage imbalance while the motor is kept running at its normal power rating, the imminent consequent will be a shortened insulation life.

- **Bearing:** This zone refers to ball or rolling element bearings in electrical motors which are one of the most common causes of motor failure. These bearings consist of an inner and outer ring with a set of balls or rolling elements placed in raceways rotating inside these rings. Faults in the inner raceway, outer raceway or rolling elements will produce unique frequency components in the measured motor's vibration or its current signature. These bearing fault frequencies are functions of the bearing geometry and the running speed. Bearing faults can also cause rotor eccentricity.

- **Stator:** The stator zone includes the DC or three-phase AC windings, insulation between the turns of the winding, solder joints between the coils, and the stator core or laminations. The stator winding consists of coils of insulated copper wire placed in the stator slots. Stator winding faults are often caused by insulation failure between two adjacent turns in a coil. This is called a turn-to-turn fault or shorted turn. The resultant induced currents produce extra heating and cause an imbalance in the magnetic field in the machine. If undetected, the local heating will cause further damage to the stator insulation until catastrophic failure occurs. The unbalanced magnetic field can also result in excessive vibration that can cause premature bearing failures as well as insulation degradation.

Localized heating around the short can also spread to other coils, resulting in a coil to coil short. Excessive heating will eventually not only destroy the motor windings, but will also damage the insulation between the laminations of the stator core. Another fault that can occur with motor windings is a phase to phase fault. This results from the insulation breaking down between two separate phases, usually lying adjacent to each other in the same slot. A higher difference in voltage potential tends to make this fault accelerate very quickly.

- **Rotor:** The rotor zone refers to rotor bars, rotor laminations and end rings. The normal failure mechanism is a breakage or cracking of the rotor bars where they join the end-rings which can be due to thermal or mechanical cycling of the rotor during operation. This type of fault creates recognizable frequency sidebands in the current spectrum around the supply frequency signal. The rotor zone, although accounts a small percentage of the motor problems, can cause other fault zones to fail. For instance, a cracked rotor bar can generate enough excessive heat to melt insulation on its lamination as well as on the nearby stator.

- **Air Gap:** This zone denotes the gap between the rotor and stator where magnetic decoupling is developed. The air gap assures efficiency if it is uniformly distributed around 360°. A non-uniform air gap results in an unbalanced magnetic fields, and thus, high vibration levels. These magnetic imbalances can cause movement of the stator windings, resulting in winding failure, and electrically induced vibration, resulting in bearing failure. To be more precise, eccentricity occurs when the rotor is not centered within the stator. This can be caused by defective bearings or manufacturing faults. The variation in air gap disturbs the magnetic field distribution within the motor and generates a net magnetic force on the rotor in the direction of the smallest air gap causing mechanical vibration.

A Partially Assembled Motor

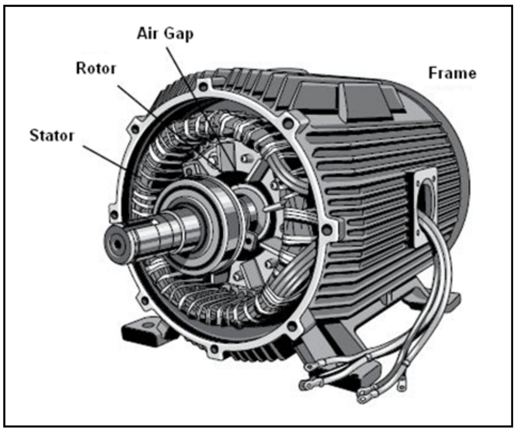


Figure 89 Schematic of a partially assembled motor [WS45]

As stated in the previous section, electrical inspection is divided to two major inspections methods: dynamic inspection or on-line testing, and static inspection or off-line testing. Each of these methods incorporates various techniques which are overviewed in this section. Starting with dynamic inspection, it has two fundamental facets: current and power analyses.

- **Current Analysis:** This technique which is also known as motor current signature analysis, CSA, is a noninvasive and online monitoring technique to identify and diagnose problems particularly in industrial induction motor (i.e. three-phase induction motors). Current analysis is based on the observation that variances in the stator-rotor air gap are reflected back into the motor's current signature through the air gap flux affecting the counter electromotive force. These changes in counter electromotive force then modulate the running current turning an induction motor into an efficient transducer. By undertaking a fast fourier transformation on motor current signatures, the power cables can act as permanently installed test leads for predictive maintenance applications. In fact, motor current analysis senses an electrical signal that contains current components that are a direct by-product of unique rotating flux components caused by faults in different parts of the motor [426], [427]. In other words, current signature analysis utilizes results of spectral analysis of the stator current, or more precisely the supply current of an induction or even a DC motor, to spot an existing or incipient failure of the motor or the drive system [328][420], [521], [522].

Detailed motor current analysis can assist in detecting and estimating the severity of electrical defects. Eccentricity, rotor bars and end ring breaks, shorted stator windings can be detected by the analysis of the stator current measurements [344]. Current analysis can detect and identify these problems at an early stage, and hence, avoid secondary damage and complete failure of the motor. Besides, startup, the most informative time in motor operation, can be recorded from start to finish. Graphing in-rush current and startup time is extremely valuable when evaluating motor operation and condition. Certain changes in the startup characteristics can be attributed to rotor or stator faults. Additionally, current profiles for operations can be recorded, trended and compared. This can be an effective method for evaluating equipment or machinery involved in plant processes. However, as Fenger et al. correctly express traditional CSA can result in false alarms and/or misdiagnosis of healthy machines due to the presence of current frequency components in the stator current resulting from non-rotor related conditions such as mechanical load fluctuations [193].

- **Power Analysis:** This technique which is also known as motor power quality analysis, PQA, is another online monitoring technique which utilizes three phase simultaneous voltage and current measurements to determine electrical equipment's in-coming power problems such as low or high voltage levels, voltage unbalances, and single and total harmonic distortions. These problems may be caused by wrong settings on supply transformer taps, poorly distributed single phase loads, overloading or saturating supply transformers, too many variable frequency drives (VFD) on low voltage busses, excessive non-harmonic frequencies on a VFD, and missing or open power factor correction capacitors. In general, lower voltages cause higher currents and therefore more heat. Higher voltages cause lower power factors and ultimately higher losses. A small amount of voltage unbalance creates an exponential amount of current unbalance which causes temperature increases. Harmonic distortion also causes thermal stress in motors. On the whole, it has to be taken into account that any of these voltage problems can cause severe overheating in the motor even without factually reaching an over-load situation [209], [410], [611].

  Power analysis allows a technician to take a power quality snapshot in order to check the condition of the voltage signal and evaluate the effect it will have on the motor or other electrical equipment. From this snapshot, the technician focuses primarily on the three phase-to-phase voltages that power the motor and determines what effect they are having on motor performance [67]. However, several disturbances that are directly associated with incoming power lines to the facility occur infrequently or on a seasonal basis. Hence, power monitoring and analysis of periods less than a year may not reveal as much as information as expected. Therefore, PQA schedules should be tailored individually according to operating time, criticality, and any other important element of operation or points of concerns. Note that there are different terminologies, either as written standards or as widely accepted, to describe disturbances appear in current and voltage signals. These terminologies may be even used at dissimilar situations by different people of diverse technical backgrounds. Graphical representations of signal disturbances like surge, impulse, notch, sag and outage are shown in figure 90. For more detailed information regarding power quality disturbances and their characteristics, it is suggested to review the work of Dwivedi et al. [171].

Current and Voltage Disturbances

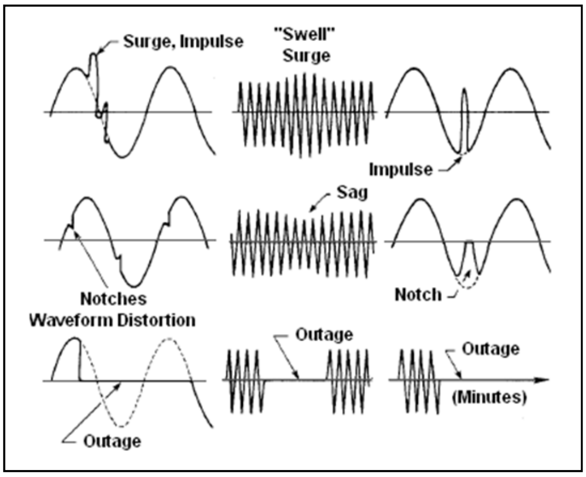


Figure 90 Schematics of different disturbances in current and voltage signals [410]

Current and power analyses are most central techniques of dynamic inspection or on-line testing. Nevertheless, there are other analyses such as torque or efficiency analysis which can additionally provide priceless information. Torque ripple and torque spectrum tests, enable the operators to identify numerous amount of problems quickly and accurately. Torque analysis facilitates diagnosing mechanical issues, determining transient overloading, and identifying soft-foot mechanical imbalances along with bearing problems [618]. Another major factor which is monitored and analyzed in dynamic inspection is motor efficiency. Efficiency is defined as the ratio between useful work performed and the energy expended in undertaking that. In other words, it is the ratio of output power divided by the input power. Efficiency is usually described by three different terminologies: nominal efficiency - the value which is assigned to a set or group of motors by the manufacturer, operating efficiency - the true efficiency of the motor as it is operating within its actual and normal environment, and minimum efficiency - the lowest efficiency value any motor within a test sample must maintain. The efficiency analysis takes in particular parameters, and calculates and monitors the operating efficiency [610]. By doing so, energy costs can be significantly cut and motor's life can be considerably extended.

Static inspection provides detailed analysis of motor and circuit condition for all types of AC and DC motors. It has been proven to improve the reliability of motor and motor-driven equipment, and significantly reduce the maintenance costs and production delays that accompany unexpected motor failures. Off-line testing of electric motors requires attaching test equipment clips at the load side of the motor control cabinet or variable frequency drive. Most test clips are the spring loaded alligator type and are easily connected to the cable ends or terminals. If the motor has surge suppressors, power factor correction capacitors, or other externally connected devices, they should be disconnected before testing as the level of test voltage applied may cause damage to these mechanisms. Each test provides vital information necessary to accurately determine the motors health; failure of any test of a particular motor part would usually result in the discontinuing of the remainder of the complementary tests. However, occasionally, a technician may wish to run a complete set of tests on a motor, even after it fails a certain test, in the hope of determining the root cause of the failure [611]. The most commonly used static tests for electrical inspection of motors include [361], [477], [478], [638], [557], [588]:

- **Bar to Bar Test:** This test examines the resistance between commutator bars in a DC motor and provides an indication of the comparative value of resistance that exists between all like electrical circuits in an armature. This aids in trouble shooting a faulty commutator or armature winding on a DC motor. The commutator consists of insulated segments assembled into a cylinder and held together by insulated rings. Electric current is transferred to the armature winding by brushes made mainly of carbon and graphite. Brush wear creates carbon dust, a conductive contaminant, which penetrates into crevices, cracks and openings of the armature. Copper particles add to the contaminant accumulation when the wrong brushes are installed or the brushes are improperly installed, or when the maintenance is inadequate. If the insulating material on the commutator bars or their risers has cracked, these contaminants can short entire windings.

- **Capacitance to Ground Test:** This test, which is commonly abbreviated as CTG test, is an indicator of the insulation condition, identifying contamination build-up on the insulation. It is also a key is sign of the cleanliness of the windings and cables. CTG capitalizes on the natural capacitance of the motor and circuit to trend dirt and moisture build-up on the insulation. It is utilized in combination with the resistance to ground measurements to determine overall insulation condition. Indeed, as dirt and contaminants build up on windings and cables, CTG values increase. An increasing trend showing rising CTG values indicates that the motor needs to be cleaned.

  Conceptually, any two conducting plates which are separated from each other by a dielectric material form a capacitor. Dielectric material is a substance that is unable to conduct direct electric current. A cable or motor winding surrounded by insulation provides one conductor and the dielectric material. The stator core and motor casing iron form the second plate. Normally, when the outside of the insulation is clean and dry, it is not a good conductor. When dirt, moisture and other contaminates begin to cover the stator windings inside the motor, they cause the outer insulation surface areas to become conductive. Since this surface is in contact with the ground, it allows an AC current path to ground. Cables in the power circuit are also subjected to the same effect, when moisture penetrates the outer casing. Over time, steadily increasing CTG values indicate an accumulation of dirt and that cleaning is necessary. This can be correlated with decreasing RTG Values.

It is central to take into account that dirt and contamination also reduce a motor's ability to dissipate the heat generated by its operation, resulting in premature aging. As generally accepted, motor life decrease by 50% for every 10°C increase in operating temperature above the design temperature of the insulation system. This holds true with the motor operating at or above a 75% load. Heat raises the resistance of conductor materials and breaks down the insulation, providing paths for unwanted current to flow to ground. If capacitance is higher than normal, a low resistance to ground reading is an indication that such a path already exists.

- **Circuit Inductance Test:** Inductance is a function of geometry and permeability. It is independent of voltage, current and frequency. In this test, the overall inductance measured is a combination of the mutual and internal inductances of the circuit, known as the circuit inductance. Fault detection is possible in winding shorts only when the capacitances of dielectric insulation systems become resistive and a shorted circuit exists, resulting in mutual inductance between the good part of the coil and the shorted turns. The advantages of circuit inductance test include the facts that basic testing may be done easily, quickly, and with inexpensive equipment. More advanced equipment is available from several vendors that are able to conduct sophisticated testing and identify problems such as voids in castings, core problems, and shorted laminations.

- **Circuit Resistance Test:** Circuit resistance is the overall DC current resistance measured through a bridge such as a Wheatstone or Kelvin bridge. Wheatstone bridge is an instrument used to measure an unknown electrical resistance by balancing two legs of a bridge circuit. Kelvin bridge is a similar instrument employed to measure an unknown electrical resistance below 1 Ohm. Its operation resembles to the Wheatstone bridge except for the presence of additional resistors to reduce measurement errors. In an integral winding, circuit resistance test is undertaken through a series of specific measurements which are analyzed in order to determine the condition of a winding. Enough measurements are required in order to compare them to each other and discern patterns. A true benefit of this test is its ability to identify problems that are located outside of the motor, but within its circuitry. These include loose connections and wiring harnesses or transformer problems.

- **Dielectric Absorption Test:** This is an insulation test by applying a one-minute voltage potential which can be performed on both AC and DC motors. A dielectric absorption ratio is calculated as the reading taken every 60 seconds divided by the reading taken every 30 seconds, and a profile of resistance to ground versus time is plotted. The developed profiles are then used to determine the condition of the motors insulation system. Utilizing detailed graphing and complete automation, dielectric absorption test along with polarization index test are used as advanced methods of evaluating insulation and can be highly effective at detecting the presence of contamination. Caution and alarm levels are set in accordance with IEEE specifications. On the whole, as the motor traps dirt and as the insulation ages and cracks, dielectric absorption ratios decrease.

- **Inductive Imbalance Test:** This test is employed to determine how well the winding impedances are balanced. In fact, an increase in inductive imbalance can indicate leakage in the stator windings or rotor faults in AC motors. Although no specific standards have been established due to the influence of the rotor on the measurement of inductance, it is generally accepted that at healthy motor condition there should be less than 7% inductive imbalance for form-wound motors and less than 12% percent for random-wound motors. In some induction motors, rotors have half of the cage shifted at their center, which tends to create an inductive imbalance of approximately 8% to 15% between phases. A rotor influence check can supplement the standard test results in signaling the presence of rotor defects since a rotor anomaly may not produce a large inductive imbalance on a single test.

- **Phase Inductance Test:** This test which is also known as phase to phase inductance test scrutinizes the circuit, stator coil and rotor components for inductive imbalances and indicates when these imbalances are at unsatisfactory or abnormal levels. Basically, high or escalating inductive imbalances designate winding faults and rotor defects. They also cause torque-induced vibration which can be linked to mechanical degradation. Also, inductive imbalance can contribute to other problems such as: bearing damage, coupling damage, loosened rotor bars, and insulation failure at winding end turns or at exit of stator slots. These phase inductance parameters can also be effectively used to identify faulty capacitors within the circuit.

In AC motors, phase to phase inductance readings can indicate the condition of the stator windings, detect phase to phase and coil to coil current leakage paths, and reveal poor or incorrect rework. The phase inductance readings can also be used to detect faults in power cables and main contacts in the power circuit. Additionally, a rotor influence check can be performed to further troubleshoot the motor to reveal faults such as: broken or cracked rotor bars or end rings; porosity and lamination damage, and eccentricity problems.

In DC motors, inductance changes within the field or armature can indicate current leakage paths in the windings. In fact, inductance changes when leakage paths develop. These paths can be either within the winding coils, or directly to ground. Leakage paths result from mechanical, thermal, environmental, or electrical damage to the insulation system of the windings. Additionally phase to phase and turn to turn shorts can occur. In either case, current flow bypasses some coils, thereby reducing inductive reactance and increasing current in other phases of the stator. Temperature rises in the remaining conductors and in the surrounding insulation, which accelerates the deterioration.

- **Phase Resistance Test:** This test which is also known as phase to phase resistance test examines the circuit and the stator coils for resistance, calculates resistance imbalance, and indicates when these imbalances are at unsatisfactory or abnormal values. High resistive imbalances indicate hot spots, high resistance connections, or coil shorting in the stator. Phase to phase resistance is the measured DC resistance between phases of the stator in an AC motor and between polarities of the armature and field coils in a DC motor. In induction AC motors, phase to phase resistance values and resistive imbalances are used for trending, troubleshooting and quality control. In DC motors, trending and relative comparison of values is employed to determine the condition of the phases in the motor and power circuits. This includes comparing readings taken from identical motors operating in similar conditions and comparing current and past readings for the same motor.

  Extremely accurate phase to phase resistance values on the micro-ohm level are recorded to determine the quality of connections in the circuit and motor itself. An imbalance figure is then calculated for ease of interpretation and trending. An increasing resistive imbalance or a changing resistance over time can indicate one or more of the following: high resistance connections; coil to coil, phase to phase, or turn to turn current leakage paths; corroded terminals or connections; loose cable terminals or bus bar connections; open windings; poor crimps or bad soldier joints; loose, dirty, or corroded fuse clips or manual disconnect switches; and, undersized conductors (i.e. misassemble or improperly engineered).

  The length, size, width, composition, condition, type and temperature of the conductors and connectors determine circuit resistance. Undesirably connected conductors, dirt, corrosion or an improper connection increases the circuit resistance. Inadequate connections also cause heating of the conductor, which increases resistance even more. This could be caused if only a few strands of a conductor or portions of a soldered joint are improperly connected to a terminal or if undersized connectors are used. In a three-phase motor circuit, the resistance in the conductor paths should be as close to equal as possible. A resistive imbalance occurs when the phase have unequal resistance. This produces uneven current flow and excessive heat.

- **Polarization Index Test:** This is an insulation test by applying a ten-minute voltage potential which can be performed on both AC and DC motors. A polarization index ratio is calculated as the reading taken every 10 minutes divided by the reading taken every 1 minute, and a profile of resistance to ground versus time is plotted. The developed profiles are then used to determine the condition of the motors insulation system. As the motor accumulates dirt during its operation and as the insulation cracks as a result of heating and aging, polarization index ratios decrease.

  In fact, there are three different currents that flow through an insulator when a voltage potential is applied. First is the charging current which starts out high and drops to nearly zero after the insulation has been charged to full test voltage. This is normally negligible after the first few seconds of the test. Second is the absorption current which starts out high and drops off in a similar way. The majority of this current dissipated after one minutes, but continues to decay for up to 5 to 10 minutes. Third is the conduction or leakage current, a small and mostly steady current which becomes a factor after the absorption current drops to a negligible value.

Leakage current should remain steady for the remainder of the test. The polarization index test allows the charging and absorption currents to decay so that only actual leakage current is measured. As a voltage is applied, healthy insulation slowly polarizes and the absorption current diminishes. This causes a steady rise in resistance until the majority of the current is from the small amount leaking to ground. In poor insulation, leakage current is high enough to surpass the lowering absorption current and provide little increase in the resistance over time.

- **Resistive Imbalance Test:** Resistive imbalance reflects the condition of the stator windings and power circuit in AC motors. It is usually caused by a loose connection on the cabling or the final connection to the motor. It may also be caused by motor lead connections on multiple lead motors if the connections are loose or in any way improperly made. For example, a one quarter turn on a bolt connecting two leads can result in an imbalance of over 3%. A resistive imbalance can cause a voltage imbalance that produces a rise in motor temperature reducing the potential life of the motor. Resistive imbalance test is for identifying existing imbalances and rectify their grounds.

- **Resistance to Ground Test:** This test, which is commonly abbreviated as RTG test, examines the ground wall insulation of the motor and circuit cables and indicates the cleanliness and health of the insulation system. It is vital to underline that as the insulation ages, cracks and small holes form, plus, it becomes brittle over time because of expansion and contraction of wiring expands due to heating and the cooling off. Besides, aging and temperature variations break down the molecular structure of the insulation. These factors allow contaminants and moisture, which collect on the surface of the insulation, to penetrate to the conductor. Since current follows the path of least resistance, some of the motor current is diverted from the motor circuit to these alternate paths, and ultimately to the ground.

  As the RTG value declines over time, CTG value often increases, which shows the presence of many current leakage paths to the ground, and thus, the accumulation of contaminants. A low RTG represents the need to clean the insulation. If the condition causing the low RTG is not corrected and the RTG value continues to decrease, the insulation could completely fail and the motor windings could be damaged. This may require a complete rewind of the stator. If the condition causing the low RTG is corrected, a less expensive motor cleaning is sufficient. RTG measurements needed to be temperature-corrected and standardized to attain precise trending of the insulation condition.

- **Rotor Influence Check:** This test, which is commonly referred to as RIC, examines the relationship between the rotor and stator fields and isolates problems to either the rotor or stator in a motor. Indeed, a motor acts similar to an electromagnet, its rotor acts like the core and its stator acts like the windings of the electromagnet. RIC shows how the rotor's residual magnetism influences the stator inductance in different positions. As the magnetic field of the rotor interacts with more of the coils in each stator winding, the inductance of the winding changes. This influence causes repeatable patterns of change in the graph of the stator inductance, shown as sinusoidal waveforms. Indeed, in this test as the rotor is turned by hand, a plot of its influence on the stator coils is developed using inductance measurements. If the influence on the stator coils is uniform, the rotor causes the effects. If the influences on the stator coils are non-uniform, the stator causes the effects. By analyzing variations in the magnetic flux and the assessing the influences on the coils while rotating the rotor, eccentricity - a non-uniformity of the air gap between the rotor and stator, rotor defects as well as the stator faults can be identified. RIC is also sensitive enough to detect excessive porosity in cast rotors, and cracked or broken rotor bars.

- **Step Voltage Test:** The information on winding condition available from a polarization index test can be considerably enhanced by observing the variation of current or insulation resistance as the test voltage is increased to the specified DC hi-pot level. If a flaw exists in the insulation, and if the ambient conditions are right, breakdown is often preceded by a sudden, non-linear increase of current with a further increase in voltage. This enables an experienced technician to interrupt the test at the first sign of such warning, and if the voltage withstand already achieved is considered sufficient, the technician returns the machine into service and conveniently schedules a future repair. A suspect winding may be identified, but the precise location of a weakness in the winding must still be found. The record of voltage versus current taken during the test can be used in future comparisons on the same winding.

All of the static inspection techniques plus current signature and power quality analyses are extremely useful in inspecting motors and other electrical equipment. However, each of these methods and techniques is effective in particular fault zones and identification of specific faults or problem-causes. For instance, a properly done motor current analysis assists maintenance technicians in identifying stator winding health, rotor condition, coupling health, bearing condition, air gap static and dynamic eccentricity, load issues and system efficiency [426]. Table 22, which is based on the information retrieved from various sources, provides an overview of the functionality of different static and dynamic inspection methods in the previously defined seven fault zones of power quality, power circuit, insulation, bearing, stator, rotor and air gap.

Table 22 Fault zones, possible faults and applicable EI tests [58], [57], [146], [307], [330], [559], [627]

Fault Zone	Possible Fault or Problem-Cause	On-line Testing		Off-line Testing
		CSA	PQA	
Power Quality	▪ Incoming voltage and current distortion ▪ Distortion in power by non-linear loads (e.g. VFDs, lighting, computers, printers) ▪ Spikes caused by VFDs and load switching	-	X	NA
Power Circuit	Loose or weak terminal connections for cables and in-line components: ▪ Over-loads or disconnects ▪ Improper materials or repairs ▪ Corroded connections at connection box ▪ Weak contact connections or pitted surfaces	X	-	▪ Phase Resistance Test ▪ Inductive Imbalance Test ▪ Resistive Imbalance Test
Insulation	▪ Deterioration by heat ▪ Moisture contamination ▪ Corrosive or solvent aerosols ▪ Current leakage paths to ground ▪ Old or embrittled insulation condition	-	X	▪ Step Voltage Test ▪ Polarization Index Test ▪ Dielectric Absorption Test ▪ Resistance to Ground Test ▪ Capacitance to Ground Test
Bearing	▪ Corrosive or deteriorating particles ▪ Dust and foreign material contamination ▪ Shift of bearing shield due to over-greasing ▪ Pitting due to voltage discharge in a short through bearing	X	-	NA
Stator	▪ Turn to turn and phase to phase leakages ▪ Partial discharges in voids in high voltage motors ▪ Deteriorated or improper connections between coils ▪ Stresses from mechanical vibration or unbalanced magnetic forces	X	X	▪ Step Voltage Test ▪ Rotor Influence Check ▪ Phase Inductance Test ▪ Phase Resistance Test ▪ Inductive Imbalance Test ▪ Resistive Imbalance Test
Rotor	▪ Broken or cracked rotor bars ▪ High resistance connections between bars and the end rings ▪ Manufacturing flaws such as porosity in cast aluminum rotors	X	X	▪ Step Voltage Test ▪ Rotor Influence Check ▪ Phase Inductance Test ▪ Phase Resistance Test ▪ Inductive Imbalance Test ▪ Resistive Imbalance Test
Air Gap	▪ Mishandled or dropped motors ▪ Dynamic eccentricity due to rotor ▪ Warping caused by uneven heating ▪ Static eccentricity by misalignment or out-of-round stator	X	X	▪ Rotor Influence Check ▪ Inductive Imbalance Test

There are different instruments which can be used for dynamic and static electrical inspections. These include devices which can measure limited variables in a particular fault zone and identify specific deteriorations and defects, or devices that have general function and can inspect different fault zones for various purposes. For instance, there is multimeter measuring voltage and resistance at micro ohm level to perform some static tests such as phase resistance or megohm-meter to carry out a resistance to ground test at mega ohm level.

Nevertheless, it has to be underline that these instruments do not provide enough information to allow most electricians to determine if an electrical problem exists. Many electricians are hesitant to restart a motor based on a single test done using a megohm-meter or multimeter, and with good reason. Therefore other testing devices are necessary to be able to look at the whole picture and to not make a quick decision. Currently, there are plenty of devices, both handheld and stationary, which perform a wide range of on-line and off-line testing. Such an instrument can be a PDA with integrated advanced cards to carry out a few special tests, or stationary but compact devices that are able to undertake different tests and analyses.

Megohm-meter, Clamp Current-meter, Multimeter

Figure 91 From left to right: a digital Megohm-meter, a clamp current-meter and a digital multimeter [WS3]

Compact Electrical Inspection Devices for On-line and Off-line Testing

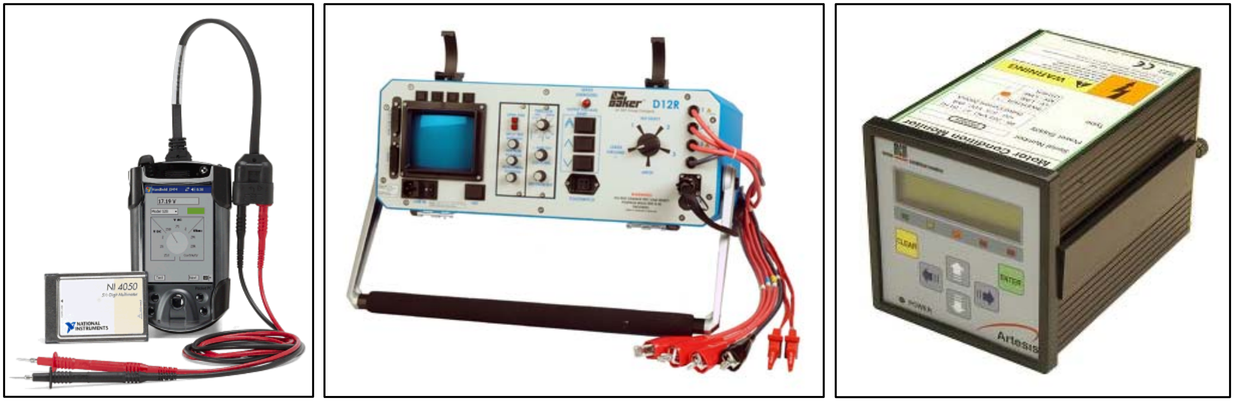


Figure 92 From left to right: A Bluetooth-enabled PDA digital multimeter [WS68], a digital off-line multi-tester [WS86], an on-line current analyzer [WS11]

In a preventive and proactive maintenance framework, it must be emphasized that motors like any other electrical device must be kept safe from harmful elements, or their performance and lifespan will be diminished. Elements such as carbon or metal dust particles, and acids and salts, are all excellent conductors. These materials, wet or dry, can conduct current at very low voltages and across very small gaps. Also, water or condensation can seriously degrade the insulation system of a motor. Water with chemicals or minerals is a conductor and can promote leakage currents, causing premature failure. In many industrial atmospheres, oily compounds are present, which are deposited on all surfaces over a period of time. These surfaces begin to accumulate contaminates, which can develop leakage currents, which result in long-term degrading of motor insulation and eventual motor failure. Besides, over temperature of motors has to be avoided by any means. Operating motors under overload conditions is one cause of over-temperature. High ambient temperatures and dirty or clogged air filters on motor-driven machine or motor blowers also contribute to over temperature failures. Inside a motor, high temperature causes expansion stress in the wire insulation, resulting in cracks, which in turn can cause contamination and eventual wire failure [486].

In fact, it is highly recommended that motor ambient temperature should not to exceed 40°C. Most motors are designed for continuous operation at this ambient temperature. Motors for use in abnormally hot places are usually designed to accommodate the higher ambient by having a lower winding and insulation temperature rise. If the ambient temperature is above 50°C, special consideration must also be made of the lubricant. For operations above 50°C, applications should be referred to the manufacturer to determine what steps must be taken (e.g. derating motor's power). Operation of motors in ambient temperature below 0°C results in severe duty on the machine component parts. Of major concern are the lubrication system and the insulation system. Altitude is another factor which is significantly important and it is usually overlooked. Standard motor ratings are based on operation at any altitude up to 1000 meters. All altitudes up to and including 1000 meters are considered to be the same as sea level. At high altitudes, derating is required because of lower air density which requires a greater amount of cooling. Depending on the magnitude, a blower may be sufficient to cool the motor instead of derating [486].

In any electrical inspection, it has to be kept in mind that faulty electrical components almost always generate heat before failing and causing an open circuit. As a matter of interest, heat is generated from an electrical component directly proportional to the square of the current passing through it multiplied by the components resistance. As the condition of the component deteriorates, its resistance increases and generates more heat and as this temperature rises so then does the resistance. This iterative process continues until the failure point of the weakest component is reached. In addition, conduction problems caused by loose connections or deterioration of contact surfaces result in local temperature rise, which contributes to the reduction of contact quality. Continuous temperature monitoring of energized equipment provides true information about the condition of the equipment. Undertaking some thermal inspections in parallel can enhance the EI test results. There are different wired and wireless, contact and non-contact technologies which can be employed for thermal inspection of electrical equipment. These vary from thermographic cameras and infrared non-contact temperature sensors to fiber optic wires which can be utilized as temperature data carriers or as active sensing elements [136], [378], [382], [422].

6.3.3 Use and Applicability

Electrical inspection is utilized to identify various deteriorations, defects and potential failure modes in three major equipment groups: motors, motor-driven machines, and devices in which electricity flows. Both dynamic and static inspection methods are used to identify and examine problems which are directly belong to motors such as eccentricity, broken bars and worn isolation. Besides, dynamic inspection techniques effectively exploit the motor itself as a sophisticated transducer to monitor the condition of the machines driven by electric motors including pumps, fans, compressors, and conveyors. This is particularly valuable for the machinery operating in inaccessible or hazardous zones.

In fact, it is a well-known incident that the greater the load on a motor, the greater the current drawn, so monitoring and assessing the current trace can provide information about the torque being demanded to drive the equipment. Similarly, speed variations in the driven machine directly affect the speed of the motor’s rotor, in turn affecting the back electromagnetic field created within the motor, and subsequently the voltage and current seen at the motor terminals where these variations can be detected. The abnormalities in these variations correspond to particular phenomena in the driven machine such as imbalance, worn bearings and cavitation. This is how monitoring of the current and voltage traces of the electrical supply to the motor can provide real information about what is happening to the driven machine. Last but not least, static inspections methods can be further employed to examine the condition of other electrical devices such as circuits, transformers and fuses.

Beginning with the dynamic inspection or on-line testing, it supplies information about the power supply, the motor and the load whilst the motor is in service. It can locate both electrical and mechanical problems that might otherwise go undiagnosed. Often motors fail and are repaired or replaced and returned to service without the root cause of the failure being determined. On-line testing can define subtle issues with power quality such as harmonics, low or high voltage, and voltage unbalance situations. Rotor bar problems, bearing issues, misalignment and many other problem areas can also be identified. Parameters to be analyzed can be monitored during definite inspection periods or continuously. Motors that begin to show obvious decline or thermal over-stressing should be monitored more closely until the motor can be tested off-line or removed from operation and repaired. New and recently repaired motors should be also tested as soon as they are returned to service in order to provide a historical record or baseline of their performance when the motor is at its healthiest condition.

More precisely, CSA can be fruitfully used to determine motor and motor-driven equipment faults. In recent years, a large amount of research has been directed toward using the motor current spectrum to sense motor faults. The monitored spectral components can result from a number of sources, including those related to normal operating condition. It is necessary to use some degree of expertise in order to distinguish a normal operating condition from a potential failure mode. This requirement is even more acute when analyzing the current spectrum of an induction motor since a multitude of harmonics exists due to both the design and the load condition. Nevertheless, the essential point about current analysis is that it senses an electrical signal that may contain current components which are a direct byproduct of unique rotating flux components caused by faults such as broken rotor bars, air gap eccentricity, bearing defect, and shorted turns in low voltage stator windings [425], [463].

It is true that, for example, broken rotor bars result in a change to the vibration spectrum, but vibration is traditionally sensed at the bearings. Plus, for each motor there is a different mechanical stiffness between the electromagnetic forces caused by broken bars and the position where the vibration is sensed. This adds a further complexity when attempts are made to quantify the severity of the problem via vibration analysis. Electromagnetic forces are inherently associated with the flux density in a motor. Thus, the vibration from unique electromagnetic forces by broken bars is a second order effect compared to current components directly induced from the specific rotating flux waves. In many cases, the fault severity (e.g. number of broken rotor bars) has to be serious before it can be detected by vibration analysis. Current analysis has been proven to be more effective and less complex in determining such problems via numerous industrial case histories [426], [455]. The motor faults that can be directly identified by motor current analysis are:

- **Rotor Bar Damage:** The reasons for rotor bar breakage are several. Rotor bar defects result in high temperatures and loss of torque in the motor. In the current signature, the motor pole passing frequency (PPF) shows up as a side band to the line frequency. The difference in amplitude between the line frequency peak and PPF sidebands is an indication of the rotor bar health [628]. Empirical research has shown that a difference of over 70 dB shows a very good rotor bar condition. As rotor bars start degrading (e.g. developing of high resistance joints or cracks), the rotor impedance rises.

  A difference of about 45 dB would indicate the presence of high resistance joints whereas a difference of about 35 dB would indicate multiple broken bars [53], [337]. It is essential to underline that starting a motor with a broken or cracked rotor bar results in generation of excessive heat to be generated in the vicinity of the broken bar. This can spread to other rotor bars and destroy the insulation around the nearby laminations and thus the stator. Unfortunately, many times broken rotor bars are not easily seen without CSA and it may be missed as the root cause of failure. This may result in a motor rewind, and replacement of bearings, but not a rotor repair. When the motor returns to service, it has the same problem all over again, just with new insulation to destroy [66].

Current Spectrum of a Motor with Different Rotor Bar Conditions

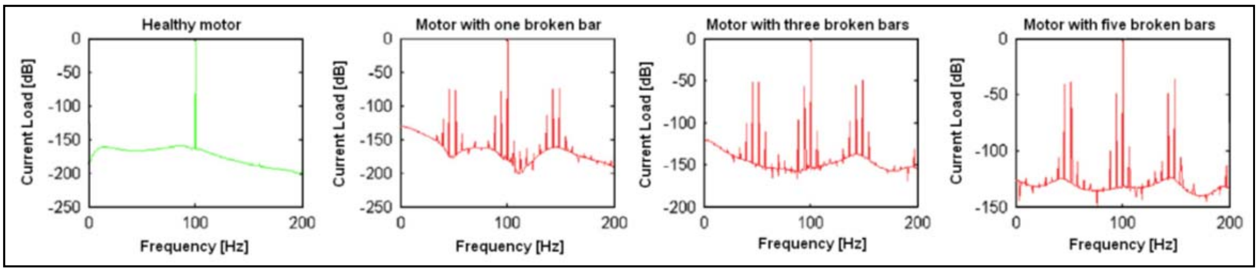


Figure 93 A motor's current spectrums in different rotor conditions working at full load [522]

It is also central to highlight that the design of a motor's rotor plays a major role in the brutality of an identified rotor anomaly. If the rotor is a closed bar design the brutality is going to be low as to the rotor iron functions in way to hold the broken rotor bar in place. On the other hand, if the rotor has an open bar design, then the relentlessness will increase significantly with the identification of a rotor defect. This elevated concern comes from the possibility of the rotor bar squeezing out of the rotor slot, contacting and thus destroying the stator.

Closed Bar and Open Bar Rotors

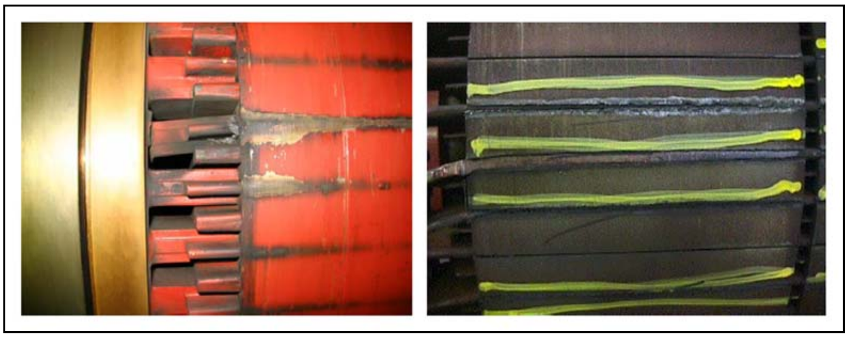


Figure 94 A closed bar rotor on the left and an open bar rotor on the right side [68]

- **Rotor Unbalance/Misalignment:** In order to identify these problems, it is required to perform another signal conditioning of motor current signal which is known as demodulation. By utilizing current demodulation, the speed of the motor can be identified as a peak in the spectrum and monitored for changes in amplitude. Based on its amplitude, it is possible to identify any misalignment or unbalance. It is notable that for an induction motor, the number of poles determines the speed of an Induction motor. A two-pole induction motor being powered by a 60 Hz line frequency runs at a speed slightly lower than 3600 RPM or 60 cycles per second (Hz). A four-pole motor runs at a speed less than 1800 RPM or 30 Hz and so on. A properly balanced and aligned motor has a frequency peak related to its speed that is barely visible. When the motor is out of balance or misaligned, this peak's amplitude will increase. As the condition increases in severity, multiples of the speed frequency are built up in the demodulated current spectrum [53], [337].

- **Air Gap Eccentricity:** Eccentricity is a condition that occurs when there is non-uniformity in the air gap between the rotor and stator. When there is an eccentricity in the air gap, varying magnetic flux within the air gap will create imbalances in the current flow, which can be identified in the current spectrum [68]. Air gap eccentricity in electrical machines can occur as static or dynamic eccentricity. Static eccentricity is defined as a stationary minimum air gap asymmetry. This can be caused by stator core ovality, soft foot in motor foundation, cocked bearing, or incorrect positioning of the rotor or stator at the commissioning stage. At the position of minimum air gap there is an unbalanced magnetic pull which tries to deflect the rotor thus increasing the amount of air gap eccentricity.

  Dynamic eccentricity is defined as a rotating minimum air gap asymmetry. It can be caused by a bent shaft, mechanical resonances at critical speeds, or worn-out bearing housing and end covers. Either can lead to a rub between the rotor and stator causing serious damage to the machine [427]. The effects of air gap eccentricity produce unique spectral patterns in the current spectrum. When there is air gap eccentricity, varying magnetic flux within the air gap creates imbalances in the current flow, which can be identified in the current spectrum. The effect of this condition is seen as multiple sidebands of odd harmonics of the line frequency powering the motor [193], [344].

  Air gap eccentricity results in increased vibration due to the uneven magnetic pull it creates between the circumference of the rotor and stator bore. Over time, these elevated levels of vibration can result in excessive movement of the stator winding, which could lead to increased friction and eventually a turn-to-turn, coil-to-coil, or ground fault. This vibration can accelerate bearing failure, which can seize the shaft and overheat the windings or allow additional movement of the shaft leading to a rotor/stator rub. The uneven magnetic stresses applied to the rotor coupled with the increased vibration will also contribute to mechanical looseness developing in the rotor. Uncorrected, this may cause catastrophic failure of the stator windings and reduce the life of the bearings [66].

- **Soft Foot/Foundation Looseness:** Motor's unbalanced foundation, distorted bedplate or loose foundation bolts cause a soft foot or foundation looseness and can later lead to air gap eccentricity in a motor. Over time a motor that is improperly mounted can develop a distorted frame due to thermal expansion and contraction as the motor heats up and cools down. Additionally, a loose motor foundation results in misalignment of motor and motor-driven machinery [53]. Soft foot can be identified by examining the demodulation current spectrum. Any foundation looseness appears as high peaks at half the running speed of the motor under inspection [337]. If the amplitude of this peak is increasing over time, the condition of the motor's foundation, mounting bolts and shims should be accurately examined.

- **Stator Faults:** Typically, these faults include loose wedges, laminations or core damage and short turns. Loose wedges damage the coil insulation mechanically and also erode the conducting varnish on the coil sides, leading to corona. The corona discharges then start degrading the motor insulation. Core damage brings about shorted stator laminations which create localized eddy currents and heat up the core locally that itself whittles away at the motor insulation and destroy it over time [337]. Inter-turn shorts cause excessive heating of the stator coil as well as formation of current imbalance which result in localized and uneven heating, reduced output and eventually a major ground fault. The current spectrum incorporates vital information about inter-turn shorts and inter-turn insulation degradation at severe levels [307], [613]. Nonetheless, detection of the stator faults is more complex and necessitates proprietary knowledge [162].

- **Bearing Faults:** The roller element bearing is one of the most crucial components in electrical motors. Rolling bearing generally consists of two rings which are called the outer raceway and the inner raceway with a set of rolling elements in their tracks. These bearings have a set of unique defect frequencies usually specified by their manufacturers which allow identification of bearing problems. When the current signature of a motor is examined, the presence of high peaks at these defect frequencies can identify the problem in terms of whether the damage is in the inner race, outer race, balls, rollers or cage [582]. The degree of degradation can be evaluated based on the amplitudes of these peaks. Besides, when the bearing is not installed properly into the shaft or into the housing, its raceway causes stator current harmonics in particular frequencies [344].

  Tandon et al. have compared different condition monitoring techniques to identify defects in induction motor ball bearings as well as grease contaminants [599], [600]. They have proven that the vibration analysis (VA) and CSA performed on the bearing of an induction motor are successful in detecting simulated defects in the outer race of the bearing. Current harmonics for bearing outer race defect has shown significant increase in the current spectrum components. The acoustic emission testing (AT) and shock pulse method are very good in detecting the bearing defect particularly as defect size increases. On the whole, AT has been claimed to be technically the best while CSA the most cost-effective technique [599]. The scholars have also shown that VA, CSA, AT and SPM measurements performed on lubricant contaminated bearings are appreciably increased as contaminant level and contaminant size increases. Among all, AT has seen to be technically the best method for this purpose while SPM is stated to be the most cost-effective technique [600].

The motor current is affected and altered by any form of vibration, which causes pulses in the torque and results in harmonics. Therefore, current analysis can also be used to identify faults or potential failure modes in the motor-driven machinery. Typical detectable defects include belt looseness, fan blade and pump vane damage, cutting tool rupture and gearbox shaft imbalance and gear tooth damage. For example, as transmitting power to the load via a belt attached to the motor changes, the variations affect current signature. By performing a CSA it is possible to identify problems like belt looseness, whose symptoms are very close to the one of a misaligned or unbalance rotor.

Moreover, fan blades and centrifugal pump vane frequencies can be monitored in a demodulated current spectrum at a frequency that is proportional to the number of blades or vanes. Increasing amplitude at this frequency as well as a possible increase at the motor speed frequency peak is an indication of possible blade or pump vane damage. In any plant, it is essential to identify the vane frequency and record its peak amplitude right after initial installation, ramp-up, or verification that the pump or fan is in satisfactory condition. Having the baseline amplitude for the equipment established in this way, the current signature can be utilized as a simple and efficient method to monitor these machines [53], [161].

As mentioned, mechanical oscillations will give rise to irregular components in the current signature. Gearboxes detrimental conditions such as shaft imbalance or gear tooth damage give rise to such current components of frequencies close to or similar to those of broken bar components. Therefore, undertaking a current signature analysis of a rotor winding for motors connected to a gearbox, the presence and influence of gearbox-related components in the signature has to be taken into account [193], [427]. It is also central to express that the operating condition of the gearbox itself is of great importance. It has been empirically shown that the current signature of a non-stationary gearbox which works under varying external load is more susceptible to load than a stationary gearbox in constant operating conditions. Thus, a new feature may be required in analyzing the current signature the motors running the gearboxes in the former operating conditions [47].

Eventually, current analysis can be exploited to detect tool wear and rupture in automated tooling and milling machines during manufacturing. Among several techniques to detect the cutting force during a tooling or milling process, motor current analysis is the most cost-effective method as it is indeed a sensorless approach by monitoring the motor current and extracting the cutting force component. It shall be added that such a signature contains undesired components in the form of high-frequency noise, current control commutation and ball screw effects which have to be filtered in order to observe the symptoms of tool defects [154], [373], [593].

PQA is also an effective method in determining motors faults, equipment driven by electrical motors and electrical systems with direct feed from electricity lines. PQA results may embrace indications of voltage imbalances, voltage spikes, excessive harmonic distortions, and stator faults. In electrical motors, high resistance connections result in voltage imbalances and excessive circulating currents. These circulating currents cause increased winding temperatures, which lead to insulation damage. Voltage spikes can be created by a number of different events, including starting and stopping of plant loads, use of solid state switching equipment such as VFD units, and power distribution system configuration changes. Significant voltage spikes stress the motors insulation system, eventually resulting in insulation failure. Harmonics are mainly caused by the use of solid state switching equipment like VFDs and also nonlinear loads. The presence of these harmonics results in excessive heating of the insulation in the motor, the distribution system, and the drive itself.

Most power quality disturbances can come from within the facility itself, such as large loads turning on simultaneously, improper wiring and grounding practices, and the start-up of large motors. These disturbances can interrupt production lines, cause damage to products and equipment, result in lost orders or transactions, corrupt data communication and storage, and cause an overall decrease in productivity in today's global economy. By monitoring the power quality at critical loads, the exact condition of the power supply can be monitored. The condition of the power at specific dates can be exploited to envisage possible downtime of sensitive machinery. Voltage fluctuation, harmonic distortion, and unbalance are good indicators to indicate the existence of these power quality disturbances. These phenomena can also designate the condition of the load and power system, and can be recorded quickly with little incremental labor using a power quality recorder [187]. PQA can be utilized to inspect and evaluate tool condition (i.e. wear severity) in various manufacturing machinery which perform machining tasks like drilling or cutting [20]. PQA is also very useful in monitoring high reliability systems such as web hosting facilities, server farms and telecommunication facilities, the common characteristic of which is tremendous downtime cost. PQA can be effectively utilized to characterize the power quality and prevent costly potential failure events [292].

Today, various motors are used to run a wide range of industrial machinery and equipment. Synchronous motors are employed in power generators, wind turbines, compressors or as gasoline engine and servo drives. Induction and wound-rotor motors are utilized to run pumps, air-handling equipment, compressors, blowers and fans, drilling machines, grinders, lathes, conveyors and crushers. Industrial DC motors are used in rolling mills, elevators, conveyors, rapid transit systems, cranes and hoists, lathes, machine tools and some blowers and fans [462]. Static inspection or off-line testing is a nonintrusive condition assessment method which can be fruitfully applied to all mentioned motor categories. The central issue is to exploit the appropriate test for the particular motor component to be inspected. Table 23 provides inclusive information on the applicability of various off-line tests to different motors and their major components. Static inspection or off-line testing can also be applied to other electronic and electrical equipment to identify problems like insulation defect.

Table 23 Applicability and fault identification of different off-line tests to different motor types and components

Off-line Test	AC Motor						DC Motor	
	Synchronous Motor		Induction Motor	Wound Rotor Motor			*Armature*	*Field (Windings)*
	Stator	*Field (Windings)*	*Stator*	*Stator*	*Rotor*	*Resistors*		
Bar to Bar Test							X	
Capacitance to Ground Test	X	X	X	X	X	X	X	X
Circuit Inductance Test		X					X	X
Circuit Resistance Test		X					X	X
Dielectric Absorption Test	X	X	X	X	X	X	X	X
Inductive Imbalance Test	X		X	X	X			
Phase Inductance Test	X		X	X	X			
Phase Resistance Test	X		X	X	X	X		
Polarization Index Test	X	X	X	X	X	X	X	X
Resistive Imbalance Test	X		X	X	X	X		
Resistance to Ground Test	X	X	X	X	X	X	X	X
Rotor Influence Check	X		X	X				
Step Voltage Test	X	X	X	X	X	X	X	X

In general, it is suggested that if a motor stops working during normal operation, the first step to be undertaken is to check for blown line fuse or tripped breaker and allow the motor to cool and try to reset in case it was running for long time. If there is abnormal vibration, it is necessary to look for loose mounting, shaft misalignment and bent shaft. In case a motor is very noisy, it is helpful to seek damaged bearings and also for rotor rub by rotating the shaft slowly by hand. Eventually, if a motor is overheated, it is essential to verify that there is adequate ventilation and that motor vent holes or fan blades are free of obstructions.

6.3.4 Limitations and Pros

Setting up and managing a program to dynamically and statically inspect the motors, motor-driven equipment, and other electrical devices within any facility is essential to insure the safe and continued operation and production in that facility. In most cases, a properly managed and operated electrical inspection program will save a plant or facility much more than it will cost to be implemented, administered and managed. An effective electrical inspection program would bring many merits but has no any known disadvantage. Some advantages of electrical inspection include:

- Minimal training costs
- Rapid identification and repair of faults
- Continuous on-line monitoring of critical equipment
- Energy cost savings by identifying inefficient motors
- Relatively inexpensive inspection and monitoring equipment
- More efficient preventive and predictive maintenance activities
- Cost effective maintenance planning by targeting identified problems
- Portable inspection systems and compact stationary monitoring units
- Improved control over electrical equipment performance and condition
- Improved reliability through analysis of failure mechanisms and modes
- Massive cost savings in comparison with other condition monitoring techniques
- Extended life of drives by identifying and addressing problems at early stage of development
- Reduction of breakdowns due to failure of motors, motor-driven machinery, and electrical devices

Indeed, monitoring of current and voltage parameters are the preconditions for developing counter measures against the problems which are associated with these elements. Once the disturbances are detected and classified, the sources of these disturbances can be determined for initiating countermeasures against equipment deterioration. By checking the current signature and power quality at critical loads, the effect of the electrical system up to the load can be seen. Overall dynamic inspection can address these issues in a number of ways.

For example, evaluation of incoming electric supply and distribution throughout the facility can determine if power quality disturbances or variations are impacting, or have the potential to impact facility operations and/or manufacturing processes. Or, monitoring and recording current and power quality trends help defining a baseline for establishing predictive maintenance activities and avoiding interruptions of critical business activities. In addition, current and power quality parameters can be correlated with motor performance and output to identify the role and effect of different components of motor and motor-driven equipment [187].

Undertaking power analysis, in particular, have entails a wide range of benefits itself. As Golkar explains, a comprehensive power analysis can ultimately result in elimination of the following problems [225]: (1) Over heating of motors other electromagnetic devices such as transformers, relays, and coils due to inductive heating effects (2) Over heating of conductors, breakers, fuses, and all other devices that carry current due to eddy currents and skin effects (3) Inductive heating of metal parts such as raceways, metal enclosures, and other ferrous (i.e. iron or steel) metal components of electrical machinery because of eddy currents (4) Voltage distortion resulting in unpredictable equipment operation due to harmonics (5) Excessive neutral current resulting in equipment overheating, excessive voltage drop, and distortion (6) Malfunction of generators and UPS systems due to voltage distortion resulting in unpredictable behavior of electric variable. It has to be stated that skin effect is the tendency of an alternating electric current to distribute itself within a conductor so that the current density near the surface of the conductor is greater than that at its core.

On the whole, proper electrical inspection provides early warnings of potential motor faults or failure of motor-driven machinery in a plant which bring about the following four major merits for a plant: (1) Safety - predicting and preventing potential failure avoid derailment of catastrophic failure modes. (2) Rapid response - delivering instant alerts directly to maintenance department or personnel results in a rapid response to defect and enables corrective actions to be carried out with minimum delay and disruption to operation. (3) Reduced maintenance costs – higher maintainability and better utilization of motors and motor-driven machinery results in elimination of sporadic failures and secondary damages, hence, resilient asset base with fewer problems and lowered maintenance needs [458]. (4) Improved long-term availability - data built up over time through electrical inspections assists in long term performance monitoring, leading to a greater understanding of the modes and rate of degradation, failure and intermittent operation, thus, better maintenance and higher availability.

Table 24 Synopsis of electrical inspection

Pros	▪ No consumables ▪ Very cost-effective ▪ Relatively easy to perform ▪ Early problem identification ▪ No part preparation required ▪ Trends of damage progression ▪ Fast, reliable and accurate output ▪ Real time measurement is possible ▪ Both online and offline condition monitoring technique ▪ Possibility of monitoring of equipment in inaccessible or hazardous zones
Limitations	▪ Some skill required for data analysis ▪ Some safety concerns while performing on-line testing ▪ Not very sensitive to particular problems such as motor bearing defects
Equipment	▪ Equipment varies from simple megohm- and multimeters to advanced portable and multitasking units.
Discontinuity types	▪ EI can result in identifying discontinuities such as porosity, stress corrosion and surface-breaking cracks as long as they deteriorate, even very small, the function of the associated equipment components. Nevertheless, the main application of EI is in identification of problems like breakage, rupture, misalignment, imbalance and looseness.
Discontinuities size	▪ They should be large enough to stress the function of the component on/in which they are located.
Relative inspection cost	▪ Equipment costs are relatively very low. The cost of electrical inspection instruments varies depending on their capabilities. A simple multimeter may cost only 10 € while the most advanced EI units may cost between 35,000 € to 40,000 €. ▪ Usually, as the test or monitoring equipment cost increases for EI the cost of training and inspection decreases. This is due to integrated software and technologies which undertake the analyses themselves and provide immediate results.

6.4 Electromagnetic Testing

Electromagnetic testing (ET), especially eddy current (EC) and magnetic flux leakage (MFL), is commonly used to inspect objects throughout their life cycle. EC techniques employs alternating currents applied to a conducting coil held close to the test object. In response, the test object generates eddy currents to oppose the alternating current in the coil. The eddy currents are then sensed by the same coil, separate coils, or magnetic field sensors. Changes in the induced eddy currents may be caused by changes to a material’s electromagnetic properties and/or changes in geometry, including the abrupt changes in current flow caused by cracks. MFL involves the use of strong permanent magnets or direct current electromagnetic field to magnetize the object of interest to near saturation flux density, and hence, can only be applied to ferromagnetic materials. Any discontinuity such as corrosion or erosion damage results in magnetic flux leakage in the test area which can be easily detected by ET [204], [531].

6.4.1 Conception

ET is basically the process of inducing a flow of electric charges, a magnetic field, or both inside a specimen and observing its electromagnetic response. If there is a flaw or discontinuity inside the specimen, it generates a measurable response. Conventionally, the term electromagnetic testing is used to refer to eddy current testing; however, with the advancement of technology, an increasing number methods and techniques came to existence. Today, there are three major tests which are classified under the electromagnetic tests group. These are eddy current testing (ECT), magnetic flux leakage (MFL) and remote field testing (RFT). ECT is used to detect near-surface cracks and corrosion in metallic objects. It is more commonly applied to nonferromagnetic materials as they have better depth of penetration of eddy currents. RTF is usually utilized for nonintrusive inspection of steel tubes and pipes. RTF is frequently exploited for inspection of pipes and tubes with smaller diameter [368].

1. *Eddy Current Testing:* This is a nondestructive test which compares the condition of a test to that of a reference standard of sound material with known defects. Its methods rely on the principles of magnetic induction, and are therefore restricted to those materials that are electrically conductive. Current loops or eddy currents are induced in a conducting material by an applied varying magnetic field. Generation and detection of eddy currents require and oscillator , a means of generating a changing magnetic field close to the part (e.g. a coil), and a means of measuring voltage in a detector. For instance, a coil of wire is energized by alternating current to produce a concentrated alternating magnetic field. When the coil is placed near a metallic component, a portion of the field penetrates into the metal and induces circulating eddy currents. The eddy currents tend to produce a magnetic field that opposes the magnetic field creating them [206], [264].

Generating and Detecting an Eddy Current

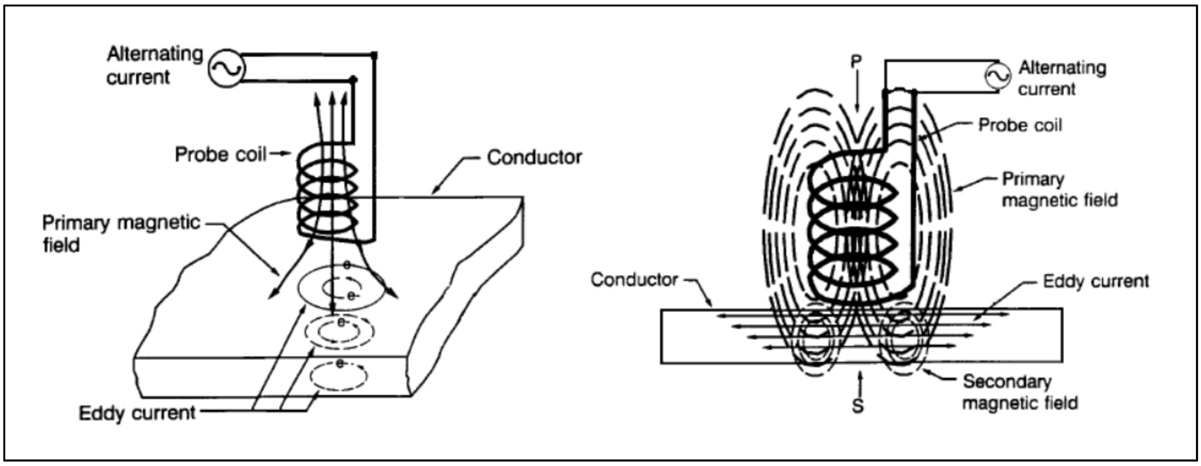


Figure 95 An abstract drawing of generation and detection process of an eddy current [190]

Changes in the characteristics of the metal, such as the electrical conductivity, magnetic permeability, and thickness will alter the eddy currents. Defects such as cracks and corrosion can also alter the eddy currents. Changes in the eddy currents cause a corresponding change in the magnetic field within and near the component. Defects and variations in the properties of the component material can be detected by measuring these fields. EC coils respond to surface dents, abrupt changes I wall thickness, and conductivity difference [264]. Indeed, the art of EC testing is to select all of the controllable parameters in such a way was to both optimally detect the desired material parameter and at the same time suppress possible signals from unwanted or non-relevant variables. Eddy current technology is mature. However, specialized procedures and equipment, which are considered horizon technologies, may be required for certain applications.

2. *Magnetic Flux Leakage:* This is a nondestructive testing method that is similar to the one of eddy current. This method involves the use of strong permanent magnets or direct current electromagnetic field to magnetize the object of interest to near saturation flux density, and hence, can only be applied to ferromagnetic materials. Any discontinuity such as corrosion or erosion damage result in magnetic flux leakage in the test area which can be detected. When ferromagnetic materials are magnetized, magnetic lines of force (or flux) flow through the material and complete a magnetic path between the pole pieces. These magnetic lines of flux start from zero at the center of the test object and increase in density and strength toward the outer surface. When the magnetic lines of flux are contained within the test object, it is difficult to detect them in the air immediately surrounding the object.

   However, if the surface of the magnetized piece is disrupted by a crack or other defect, its permeability is drastically changed and leakage flux will emanate from the discontinuity. By measuring of the intensity of this leakage flux, the severity of the defect can be determined to some extent. The MFL technique does not require contact and can be automated for high speed testing. MFL is usually regarded as a qualitative technique, although some estimates of defect size can be made. Thus, MFL is largely a screening tool which can be followed by ultrasonic inspection for determination of defect size.

3. *Remote Field Testing:* Remote field testing (RTF) is another electromagnetic testing method which is commonly employed. Remote field testing is usually associated with eddy current testing; however, there exist several major differences between these two methods. RTF is specifically employed to inspect ferromagnetic tubing. In this method, a probe consisting of an exciter coil and one or more detectors is pulled through the tube. The exciter coil and the detector coil are fixed at an axial distance of two tube diameters or more in between. Then the exciter coil is driven with a relatively low frequency sinusoidal current to produce a magnetic field. This changing magnetic field induces strong circumferential eddy currents which extend in axial and radial directions. These eddy currents, in turn, produce their own magnetic field. The exciter field is stronger near the exciter coil and the eddy current field becomes dominant at some distance away from the exciter coil. The receiving coils are positioned at a distance where the magnetic field from the eddy currents is foremost, i.e. unaffected by the magnetic field from the exciter coil but can still adequately measure the field strength from the secondary magnetic field. Electromagnetic induction occurs as the changing magnetic field cuts across the detector coil array. By monitoring the evenness of the voltage induced in the detector coil one can spot the discontinuities in the test object.

Remote Field Testing

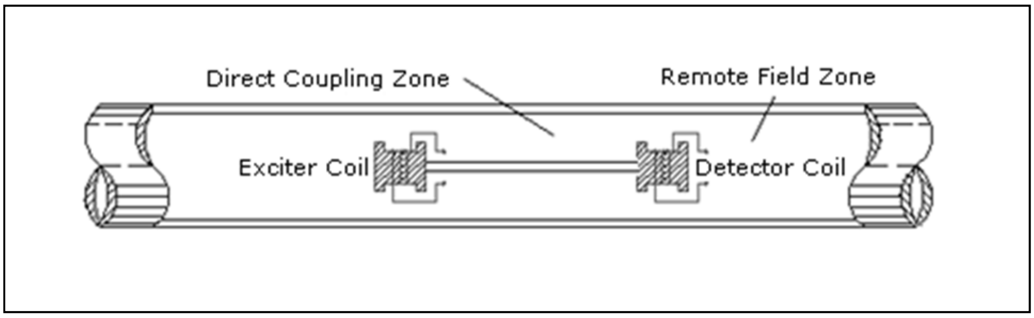


Figure 96 A schematic showing location of remote-field zone, where direct coupling between the exciter and the receiver coils is negligible, in relation to exciter coil and direct coupling zone, where the magnetic field from the exciter coil is interacting with the tube wall to produce a concentrated field of eddy currents [675]

6.4.2 Tools and Techniques

Eddy current sensors are electrically and mechanically robust devices designed to measure the proximity of conducting surfaces with high resolution in both distance and time. A wide variety of EC coils and probes is available. Coils and probes are not always interchangeable between various types of instruments and, for best results, should be matched to a specific instrument and frequency range. Special probe holders can be fabricated to facilitate eddy current inspection of contoured or shaped parts including part edges. Indeed, one of the major advantages of eddy current inspection is that probes can be custom designed for a wide variety of applications [206].

Eddy current instruments can be purchased in a large variety of configurations. Both analog and digital instruments are available. Instruments are commonly classified by the type of display used to present the data. The common display types are analog meter, digital readout, impedance plane and time versus signal amplitude. Nonetheless, it has to be taken into account that using any instrument in manual scanning, signals are affected by unwanted variations of scanning speed and alterations of probe position; hence, these effects have to be eliminated by any means [570].

Magnetic flux leakage probes respond to surface flaws. Changes in the cross section, perhaps associated with cracks, corrosion, reduced wall thickness, or other defects, can be measured by monitoring the magnetic flux density using magnetic sensors. Magnetic flux leakage tools and techniques are mature and well developed in industry. Nevertheless, as Sophian et al. underline, in the situations where defects may take place on the near and far surfaces of the structure under inspection, current MFL techniques are unable to determine their approximate size; therefore, an extra transducer may have to be included to provide the extra information required [579]. Besides, traditional techniques are rarely effective when the shapes of the specimens and defects with respect to the applied field are arbitrary. In order to overcome such pitfalls, measurement of the three-dimensional magnetic field is recently employed [19], [374], in addition to pulsed MFL technique [579].

Remote field probes are of different types using either a single or dual excitation coil to develop an electromagnetic field through the pipe or tube. The excitation coils are driven by alternating current. Probes can be used in differential or absolute modes for detection of general discontinuities, pitting, and variations from the inner diameter in ferromagnetic tubing. To insure maximum sensitivity, each probe is specifically designed for the inside diameter, composition, and the wall thickness of a particular tube. Besides, instruments used for RFT inspection are often dual use EC and RFT instruments employing multi-frequency technology. The excitation current from these instruments is passed on to the probe that contains an exciter coil. The receiving coil voltage is typically in the microvolt range, so an amplifier is required to boost the signal strength.

6.4.3 Use and Applicability

Eddy current techniques are particularly well-suited for detection of service induced cracks in the field. Service induced cracks in machinery structures are generally causes by fatigue or stress corrosion. Both types of cracks initiate at the surface of a part. If this surface is accessible, a high-frequency EC inspection can be performed with a minimum of part preparation and a high degree of sensitivity. If the surface is less accessible, such as in a subsurface layer of structure, low-frequency EC inspection can usually be performed. Eddy current inspection can usually be done without removing surface coatings such as primer, paint, and anodic films. ECT has the greatest application for inspecting small localized areas where possible crack initiation is suspected rather than for scanning broad areas for randomly-oriented cracks. However, in some instances it is more economical to scan relatively large areas with eddy current testing rather than strip surface coatings [245], [675].

Typical Surface and Subsurface Cracks

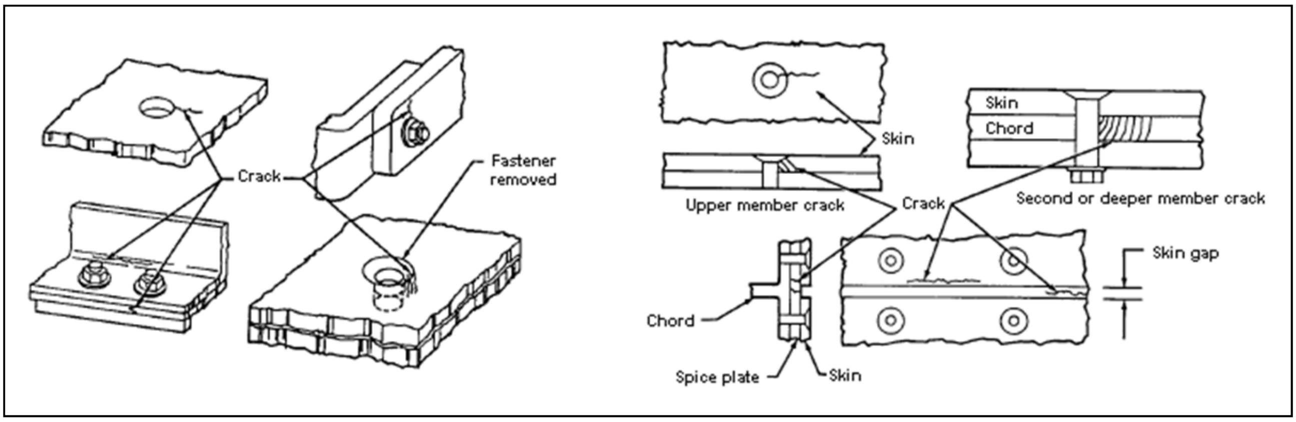


Figure 97 A schematic presenting examples of typical surface and subsurface cracks close to bolt-screw holes in different structures [190]

Electromagnetic techniques such as eddy current are also employed in wire-rope examination in many countries round the world. Much of the original development work was done in connection with mining ropes but now the techniques are being used much more widely in different manufacturing industries. These can be used on both running and stationary wire-ropes and indeed electromagnetic testing is the only practical method to monitor the condition of long lengths of wire-ropes quickly. It can also be used to detect defects in the plastic-covered steel-wires or in wire-ropes covered by thick coating of lubricant. It cannot however be used to examine the short vulnerable length of a rope close to an end fitting, and it can only be applied to wire-ropes, strand and cables made from magnetic materials [137], [138].

Magnetic flux leakage approach is applicable to ferromagnetic materials such as iron and some steel alloys that support a relatively large flux density in the presence of a relatively small applied magnetic field. The total flux density found in a circular test object (e.g. a pipe) encircled by a magnetic drive coil is a function of the filed intensity and the cross section of the test object. MFL has been used in measuring cross-sectional loss in wire ropes, testing pipes in different processing plants, detecting defects in in-service oil well tubing, and assessing quality in the production of pipes for oil field use. For example, Drury and Marino declare that the probability of detecting isolated pitting is greater with MFL than ultrasonic testing [167].

In the case of pipelines or well casing, pigs mounted with a circumferential array of MFL detectors are used for on-line inspection. MFL pigs are also available for a range of internal diameters, including small diameter heat exchanger tubes. An example of MFL inspection of piping is given by Stalenhoef et al. [583]. Elevated temperature testing requires electronics that withstand such temperatures. The accuracy of commercially available inspection tools is typically 5 to 10 percent of wall thickness for general type corrosion and 10 to 20 percent of wall thickness for pitting.

RFT, on the other hand, is mostly used to inspect ferromagnetic tubing since conventional eddy current techniques have difficulty inspecting the full thickness of the tube wall because of the strong skin effect in ferromagnetic materials. The RFT method has the advantage of allowing nearly equal sensitivities of detection at both the inner and outer surfaces of a ferromagnetic tube. The method is highly sensitive to variations in wall thickness and tends to be less sensitive to fill-factor changes between the coil and tube. RFT can be used to inspect any conducting tubular product, but it is generally considered to be less sensitive than conventional eddy current techniques when inspecting non-ferromagnetic materials.

6.4.4 Limitations and Pros

All in all, ET methods are highly effective for the detection of cracks present on (inner or outer) or below the surface of metallic objects. ET equipment has become extremely portable and is relatively cheap. Recent advances in eddy current technology include multi-channel portable instruments, allowing faster inspections of large areas, and new magnetic sensors, such as the giant magneto-resistive sensors (GMR) developed for computer hard drives, instead of coils [204].

Table 25 Synopsis of electromagnetic testing

Pros	▪ Moderate speed ▪ Immediate results ▪ Quantitative flow sizing ▪ Sensitive to small discontinuities ▪ Portable and suitable for field applications ▪ Can be automated for repetitive inspections ▪ Detects both surface and subsurface discontinuities	
Limitations	▪ Rough surfaces interfere with test ▪ Surface must be accessible to the probe ▪ Relatively high skill and training required ▪ Time consuming for inspection of large areas ▪ Only electrically conductive materials can be checked ▪ Not effective for cracks deep in thick sectioned metallic materials ▪ Sensitive to correct use of flux and current level for item under inspection ▪ In case of use for ferromagnetic materials, the item must be magnetically saturated	
Equipment	▪ Except for simple equipment, most have computer control and data logging ▪ Specialized equipment is available (e.g. for conductivity measurement, etc.) ▪ Automated scanning and single frequency or multi frequency equipment are also available	
Discontinuity types	▪ Void ▪ Hole ▪ Burst ▪ Crack ▪ Seam ▪ Pitting ▪ Inclusion ▪ Corrosion	▪ Impact wear ▪ Stress crack ▪ Broken fiber ▪ Delamination ▪ Surface-breaking ▪ Subsurface-breaking ▪ Stress corrosion crack
Discontinuities size	▪ It depends on geometry but down to 0.5 mm for fatigue cracks at or near surface	
Relative inspection cost	▪ It can be labor intensive if used manually on large areas ▪ Equipment costs vary from a modest amount to 70,000 € or more	

6.5 Laser Inspection

With development of various laser based devices for various condition monitoring and nondestructive applications, the importance of laser inspection (LI) has been progressively become clearer. For example, laser alignment can be effectively utilized to correct misalignment of shafts, couplings and other rotating machinery. It also helps industries with significant energy savings through precise alignment of their rotating assemblies. Other laser inspection methods such as laser shearography enable maintenance professionals to identify critical defects on expensive machinery parts before a catastrophic failure occurs.

6.5.1 Conception

The term laser is an abbreviation for light amplification of stimulated emission radiation. Indeed, laser is an intensive single wavelength light which is unidirectional and very stable. Currently, there is a wide range of lasers with different wavelengths that are used for various commercial purposes. In the below figure, laser types with distinct wavelengths are shown above the axis, while the lasers that can emit in a particular wavelength range are presented below the axis. Continuous wave (CW), pulsed and diode stacks emissions are represented by solid, dotted and lined bars or areas respectively. The length of the bar or area is an indication of the maximal power or pulse energy commercially available. For a better presentation of the visible region, different regions on the wavelength axis are highly distorted in length.

Wavelengths of Laser Lines for Commercial Use

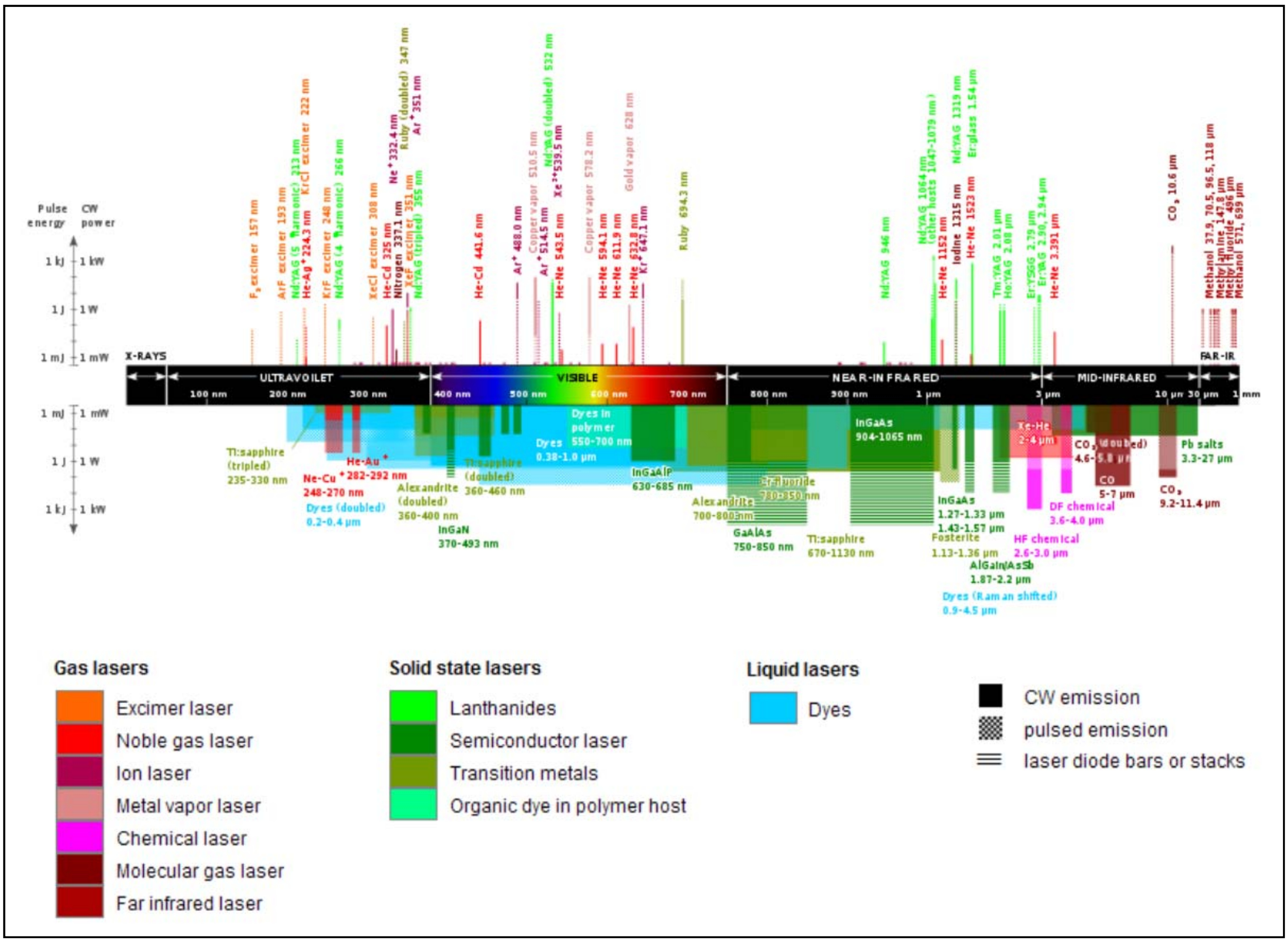


Figure 98 A graphical representation of various laser types [323]

One of the classical types of lasers is the helium-neon laser. He-Ne laser apparatus consists of a crystal tube filled with He-Ne gas lasing medium. Two reflective mirrors are at the ends of the tube, one of which is flat and the other is semitransparent through which laser radiation is emitted. When a high voltage source is applied across the tube, helium atoms are excited by the electron flow. The excited atoms collide with neon atoms that progressively decay to slightly lower energy levels and create photos. Photons are reflected back and forth by the mirrors which rouse the emission of more and more photons. Some of the created photos are absorbed by ground potential electrons that themselves become excited and generate photons again. When the rate of photon emission exceeds the rate of photon absorption, stimulated emission occurs and a coherent beam of light is created which has a fixed amount of amplification [438].

The safety issues associated with laser inspection is quite similar to that for radiographic testing or other nondestructive tests and condition monitoring techniques which get use of dangerous electromagnetic radiation. Based on the safety concerns lasers are classified into five distinct groups as explained in the next page [438].

- *Class 1* - These lasers are considered to be incapable of producing harmful radiation levels and are therefore exempt from most control measures.
- *Class 2* - These lasers emit radiation in visible section of the electromagnetic spectrum. They generate bright light and are generally not directly viewed for extended period of time.
- *Class 3a* - These lasers would not normally produce injury to the unaided human eye if viewed momentarily. They may present a hazard if viewed using light collecting optical devices. An example is He-Ne laser with up to 5 mW of radiant power.
- *Class 3b* - These lasers can cause severe eye injuries if viewed directly or if specular reflections are looked at. Class 3 lasers are normally a fire hazard. An example is He-Ne laser having radiant power between 5 mW and 500 mW.
- *Class 4* - These lasers are hazardous to the eye from both direct and reflected beams. In addition they can damage skin and cause fires. It is notable that irreparable retinal damage can happen instantly with class 3b and class 4 lasers.

There are different laser inspection methods that each of which is suitable for particular application in maintenance of various machinery and objects. These methods include: laser alignment, laser holography, laser profilometry, laser shearography and laser vibrometry. These laser inspection methods are briefly described in the coming pages.

1. Laser Alignment: This method is the process of checking and correcting the relative positions of two or more machinery shafts connected and running together at any one time within a tolerated margin using laser equipment. Misalignment between the drive and driven shafts of rotating machinery causes excessive vibration and is therefore one of the major causes of premature bearing failure. It is also known to be the main cause of premature seal and coupling failures. All shaft misalignments can be identified as parallel, angular or a mixture of both. In the case of parallel misalignment, the centerlines of the shafts are parallel but they are offset while in angular misalignment, the shafts are positioned at a relative angle to each other. Indeed, angularity is simply the angle between the shaft centerline of the stationary machine and the machine to be moved, in both the horizontal and vertical planes independently. Horizontal misalignment is misalignment of the shafts in the horizontal plane and vertical one is misalignment of the shafts in the vertical plane [557].

Taking a motor-pump system as an example, parallel horizontal misalignment is where the motor shaft is moved horizontally away from the pump shaft, but both shafts are still in the same horizontal plane and parallel. Parallel vertical misalignment is where the motor shaft is moved vertically away from the pump shaft, but both shafts are still in the same vertical plane and parallel. Similarly, angular misalignment can be categorized into horizontal and vertical misalignment. Angular horizontal misalignment is where the motor shaft is under an angle with the pump shaft but both shafts are still in the same horizontal plane. Whilst, angular vertical misalignment is where the motor shaft is under an angle with the pump shaft but both shafts are still in the same vertical plane [484].

Different Types of Misalignment

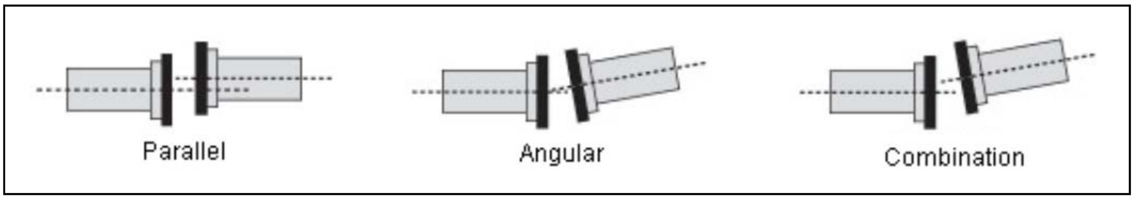


Figure 99 Different misalignment conditions: parallel or offset, angular and combination of both

2. Laser Holography: This method, which is also known as holographic interferometry, gets use of the ability to capture two slightly different images and flaunt the small differences between them. The image of an object stored in holographic film is made to interfere with another image of the same object, or with the object itself, creating sets of contour lines. These lines, commonly referred to as interference fringes, are a measure of the amount of dimensional differences of the object at two different states. Since internal anomalies change the way an object responds to external stress, the irregularities of the contour lines are usually obvious even to untrained observer [667].

Inspection of the fringe pattern arising from strain perturbation caused by the application of thermal or mechanical loads, gives a considerable amount of information on the type and magnitude of surface movements. If a flaw is present in the real object, either on the surface or beneath, it disturbs the contour lines pattern which is developed as a result of the image interference. The disturbance observed is in the form of abrupt changes or discontinuities on the contour lines. It is possible therefore to locate the position, orientation and densities of the flaws and irregularities without contact being made. Crack detection and the location of disbonds in composite materials are applications for which holographic interferometer has been found to be very useful [164].

Holographic Image and Discontinuities

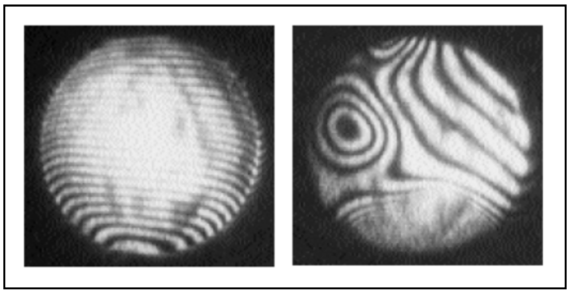


Figure 100 Holographic images of a correctly bonded structure on the left and a poorly bonded structure due to discontinuities which are seen as irregularities in the fringe pattern on the right [191]

3. Laser Profilometry: This method, which is also known as laser scanning, involves traversing an object's surface with a laser senor. It incorporates point sensors along with highly precise stages to create two-dimensional surface profiles and record the profiles with respect to the travel time or the traveled distance. In fact, the specimen, which is inspected by the sensor, is moved by the stages while the sensor transmits the height data to the measurement control unit. To improve lateral accuracy, the sensors are synchronized to the stage movement. These profiles are then diverted to three-dimensional topographic maps which can be analyzed by specific software to identify surface flaws or discontinuities. In recent years, numerous laser profilometry systems have been developed for various applications, particularly for inspection of tubing and pipes [408].

4. Laser Shearography: This method employs the coherent, monochromatic features of laser light to create speckle patterns. The specimen is illuminated by the laser. The surface reflects the light creating a speckle pattern at the viewing plane, which can be processed to provide information such as the presence of defects, material degradation or residual stress. The system records the speckle pattern from an unstressed specimen surface. The image is recorded using a video camera and subsequently it is digitally stored. Then, the specimen surface is stressed and a new speckle pattern is created, recorded and stored. Software deducts the two recorded speckle patterns from each other and generates an image made up of series of characteristic black and white fringes that represent the surface strain in the area of interest. If the specimen surface or subsurface holds any kind of discontinuity such as a void or disbond, it impinges on the surface strain and thus the discontinuity can be revealed by the generated fringe pattern [566].

5. Laser Vibrometry: This method utilizes laser based vibration transducers or laser vibrometers, which require no physical contact with the test object. The measurement principle of a laser vibrometer is based the doppler effect, which can be illustrated by the acoustical tone of a moving vehicle which changes as it overtakes another vehicle on autobahn. Since the light propagation can be construed in an analogous way, the same physical principle is applied as in acoustics. When monochromatic laser light is scattered back from a vibrating object it endures a frequency shift proportional to the velocity of the object; this is known as the doppler effect for a laser light [492]. If the object budges towards the light source, the frequency of the back-scattered light rises. If the object budges away, the frequency falls. When the object vibrates, the frequency of the back-scattered light is the frequency modulated at the so-called doppler frequency, which is directly proportional to the object's velocity. For this reason, tracking the doppler frequency provides a direct measurement of the object's velocity relative to the motion of the light source. This principle can be exploited in laser systems measuring both translational and angular vibration. Non-contact inspection of objects that are dangerous, difficult or impossible to access is where laser vibrometry is typically used [163].

6.5.2 Tools and Techniques

There is a wide range of advanced laser sensor systems for quantity measurements, guiding, navigation, pattern recognition, and vision systems for manufacturing and maintenance purposes. Historically, in the field of LI, one of the focuses has been on improvement of the laser systems for distance gauging and displacement measurements. The triangulation geometry is the most popular one and the range determination can be done by triangulation method applied to the detection direction determined by the light position on the detector. In addition to measuring distance, several other parameters can be measured by using laser-based sensor systems. Laser can be used as a coherent light source for the optical sensors, specifically, some systems that operate based on the interference principle, which requires a very coherent light beam [30], [144].

The typical helium-neon laser is utilized to generate a visible line, which can be used for positioning an object, surveying, and guidance of equipment. The use of a beam light for alignment, which is called optical tooling, has many advantages in comparison with mechanical alignment methods. Other methods are slow, cumbersome and require more than one operator. Optical tooling has developed since the advent of the lasers and sensitive optical detectors. The new devices are designed so that in addition to alignment, tasks such as angular alignment, definition of planes, leveling and fixing of right angles can be readily performed. Besides, laser range finders are employed to measure distance by projecting a beam to a target whose distance from the laser source is to be measured [227].

Laser vision systems are intelligent sensor systems for complex measuring or inspection tasks such as: image acquisition, processing, segmentation, and pattern recognition. The role of image acquisition subsystem in such system is to transform optical image data into an array of numerical data, which can be assessed and worked out by a computer. Laser vision systems have played a significant role for product, machinery and equipment inspection in industry. Applications range from spot inspection in auto body welding to palette label checking in the manufacturing industry. A laser visual system enables the following operations: image acquisition and analysis, recognition of certain features or objects within that image, and the exploitation and imposition of environmental constraints [175], [226], [278].

Table 26 Laser types and their system usability in industry [227]

Laser Type	System Usability
AlGaAs (810 nm)	Range finder, Vision system
He-Ne (632.8 nm)	Distance and angular rotation measurer, Range finder
InGaAsP (1300-1500 nm)	Range finder
Nd:YAG (532 and 1064 nm)	Range finder

Laser alignment systems vary for different applications of aligning coupled shafts in motors, pumps, ventilators and gearboxes with rolling bearings. However, usually these systems contain a laser transceiver and reflectors (or a laser transmitter and receiver), different gadgets and mechanism such as brackets, chains, posts, sockets for mounting the laser devices on the machinery to be examined and a processing unit (e.g. a computer and software) to analyze the signals and align the mismounted components like shafts and bearings. Before any alignment operation, any soft or tilting foot (i.e. machine foot that lifts off the floor when slackened) should be corrected in order to prevent increased vibration tendency and bearing damage due to housing distortion.

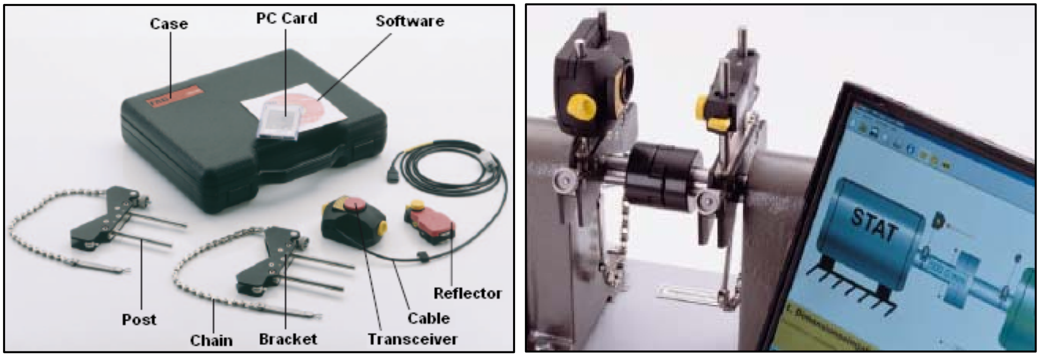

Laser Equipment for Shaft Coupling Alignment

Figure 101 Different components of a laser equipment kit which is used for shaft coupling alignment [WS84]

Laser holography is a method to record both the amplitude and phase of the light wave scattered by an object. It used to record holographic images on photographic plates more than a decade ago. However, with the emergence of high resolution charge coupled devices (CCD) and the improvement of processing capacity of computers, digital holography which is a way of digitally recording and numerically reconstructing a hologram, has taken the place of conventional holography in many applications. Digital holography can be done in almost real time since there are no wet chemicals and time-consuming procedures to create and process the holograms. Via numerical reconstruction, it allows high flexibility on controlling some imaging parameters such as focus, size and resolution [342].

Holographic interferometry incorporates three techniques: Real-time holography, which consents to instantaneous observation of the effects of minute changes in displacement on or inside an object while some stress is applied on it. This is done by superimposing a hologram of an unstressed object on the stressed one. Multi-exposure holography creates a hologram by using two or more exposures. The first exposure shows an object in an unstressed condition. Subsequent exposures, recorded on the same image, are made while the object is subjected to some stress. The resulting image depicts the differences between the initial and proceeding conditions [164], [240]. Time-average holography involves creating a hologram while the object is subjected to some periodic stress. In this technique, a single hologram is created using a laser that incorporates some closely spaced frequencies, yielding separate interference patterns on the same plate. When a single laser frequency subsequently reconstructs the hologram, the images interfere to generate a pattern of fringes that map the depth of the object which provides a dramatic visual image of the vibration pattern. All these techniques reveal the shape and direction of the stress induced displacements, and thus, the possible defects [191].

Laser profilometry involves traversing a surface of interest with a laser sensor. In this technique, a diode laser produces a collimated beam of light, which is then projected onto a target surface. A lens focuses the spot of reflected laser light onto a photo-detector, which spawns a signal that is proportional to the position of the light spot on the detector. The detector captures 2D surface profiles of the surface under inspection and the system records the profiles with respect to the time or distanced travelled. Based on the fact that as the height of the target surface changes, the image spot shifts due to parallax, the 2D surface profiles are compiled into a 3D surface topography may that can be precisely analyzed by particular software enabling identification of surface discontinuities or flaws. With the use of miniature optics, higher speed signal processing electronics, and advanced computer data processing and graphical software, various laser profilometry systems have been developed for a broad range of applications from inspection of pipes and tubes to identification of weld anomalies [510], [519].

A Desktop Laser Profilometer

Figure 102 A desktop laser profilometer for inspection of small objects [WS87]

Laser shearography is a very sensitive method that is able to visualize the strength of an object under inspection. The system consists of miniaturized shearography sensors, an integrated high-resolution CCD camera with shearing lens and variable computer controlled shear optics to view laser light reflected from the object's surface. The required illumination is generated by an integrated diode laser array and the whole system is controlled from a connected computer. Sheared images are captured and overlapped to bring two separate points on the object's surface to meet in the image plane. The two overlapped portions of the sheared images interfere and produce a pattern. The two speckle patterns (i.e. stressed and unstressed) are used to create a fringe pattern which depicts the relative displacement of the two neighboring points.

This highly sensitive interferometric technique determines microscopic surface deformations caused by internal flaws when a small loading is applied to the object. This can be undertaken using thermal, pressure, vibration or mechanical excitation. The results are displayed live as the material responds to the excitation and are easily interpreted by the operator. It is essential to underline that since the magnitude of image shearing is small, the fringe patterns approximately represents the derivative of displacement (i.e. strain) with respect to the shearing direction. This differentiates shearography from holography, which depicts displacement rather than its derivative [584].

Laser Shearography System

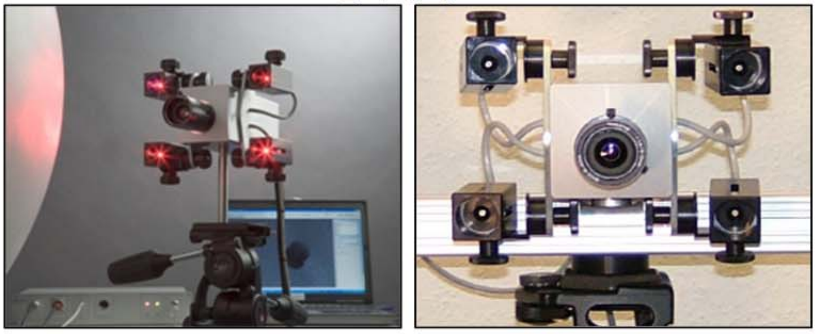


Figure 103 A portable laser shearography system with a small sealed camera and multiple diodes [WS30]

Laser vibrometry is a sophisticated non-contact vibration measuring method particularly useful when alternative methods either reach their limits or simply cannot be applied (e.g. vibration measurement of high speed rotational equipment or very small and light objects). It utilizes laser doppler vibrometers (LDV) that operate in a very wide range of vibrational spectrum with very linear phase response and high accuracy, rather than contacting transducers that can fail when attempting to measure high amplitudes and are also subject to wear and slippage. The LDVs' standoff distance, which is usually between 0.5 and 300 cm, allows fast and convenient repositioning of the laser probe and enables accurate vibration measurement of operating machinery at several locations without interruption. The laser source in most of the LDVs is either a He-Ne gas laser generating visible red light or a solid state laser diode generating infrared light, although, Nd:YAG lasers are also seldom used. In any case, the energy level of the laser light is low, ensuring a safe instrument that can be operated with minimum safety precautions [40].

Conventionally, an LDV is a two beam laser interferometer that determines the frequency or phase difference between an internal reference beam and a test beam. The laser beam is pointed at the specimen's surface and the scattered light from the object is collected and interfered with the reference beam on a photo detector. The vibration amplitude and frequency are extracted from the doppler shift of the laser beam frequency due to the motion of the object's surface. The output of an LDV is a continuous analog voltage, which is proportional to the object's velocity component along the direction of the laser beam. There are various types of vibrometers in the market. Figure 104 indicates a single point LDV which has been made by the company Brüel & Kjær. This compact and rugged vibrometer, with its integrated digital decoding technology, is particularly designed for difficult surfaces with low reflectivity, poor light scattering characteristics and for the analysis of low vibration amplitudes.

A Single Point LDV

Figure 104 A single point LDV with integrated digital decoding technology [WS18]

Many industrial machines such as engines, power trains and gearboxes are significant sources of rotational vibrations. These machines undergo rotational motion and mechanically transmit the torque, movement, speed and acceleration from one place to another. In addition to generating torsional and bending vibrations while undergoing rotational motion there are many vibrations created in its transmission to the point of usage. Additional vibrations are generated by mismatched gearing, unbalanced shafts, and poorly aligned articulate joints. All of these unwanted vibrations result in undesirable noise and premature fatigue of the mechanical systems. Rotational vibrometers measure torsional and bending vibrations up to an operational angular-velocity of 20,000 RPM. For rotational LDVs, since the sensor uses light as the probe, no inertial mass is added to the rotating part and no telemetry is needed to acquire highly accurate and reliable data.

Figure 105 shows a rotational LDV system which has been made by the company Polytec. The LDV's sensor head is consisted of two functional sections: the laser unit and the compact sensor. The laser unit includes a He-Ne laser and two high-precision interferometers for converting minute frequency changes of the reflected laser light into electrical signals. These signals are then decoded in the LDV's controller. The outputs of the decoding process are voltage signals proportional to the real-time angular velocity and, by integration, angular displacement. The compact sensor can be optimally positioned in minutes using a removable balance indicator, which is the oval component shown in the image on the right. The head can be exposed to high temperatures, dirt and moisture without any difficulty.

A Rotational LDV

Figure 105 A rotational LDV with an integrated air purge system to cool its sensor head and prevent contamination from oil spray and dust [WS79]

6.5.3 Use and Applicability

The most well-known application of laser inspection is in precise alignment of different rotating machinery. Alignment is a process of checking and correcting the relative positions of two machines connected and running together at any one time, such as a pump and motor. If the rotating machinery is not thoroughly checked for parallel and angular misalignment in horizontal or vertical planes, they might be operating inefficiently. Besides, the reliability of rotating machines can be considerably increased if regular laser inspection for possible misalignments is undertaken. Laser alignment can be effectively utilized to correctly position and connect shafts in various mechanical assemblies, bores and bearings, gears and gearbox systems, lathes and spindle axes, and rolls. It is essential to underline that laser alignment contribute to large energy savings and environment-friendly production [484], [487].

Coupling Alignment on a Chill Water Pump

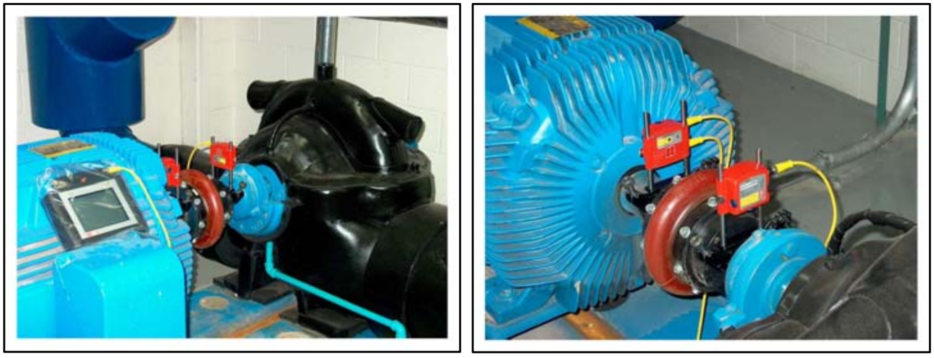


Figure 106 Photos of mounted laser alignment devices on a chill water motor-pump system [WS53]

Another application of laser alignment systems is aligning belt transmissions. Such a system usually has two line laser transmitters, each equipped with two spring loaded guides which fit into the pulley grooves of standard sheave sizes of 6 to 40 millimeters. Additional guides are also available for alignment of timing belts with different groove shapes and sheave sizes. By using the groove as reference the operator can achieve a precise alignment which reduces belt wear, bearing failures and vibrations. The use of two laser transmitters with integrated targets makes it very easy to determine the type of possible misalignment: parallel offset, angular error and twist is instantly visible to the operator.

Belt Transmission Alignment

Figure 107 Laser belt alignment systems with laser transmitters that fit into the pulley grooves [WS38], [WS84]

Holographic interferometry is a LI method to precisely measure static and dynamic displacements of objects with optically rough surfaces. It is also employed to create contours representing the form and flaw characteristics of the object's surface. Laser holography is also be used to detect optical path length variations in transparent media. It can identify the changes in phase of light beam and density of gases, liquids and solids. It has been widely used to measure stress, strain, and vibration in various industrial machinery and engineering structures. Bending of metallic bars and plates, and thermal expansion of metallic tubes can be determined particularly if they have been made from light metals such as aluminum. This method is so extremely sensitive that can disclose peculiarities in the objects' inner structure such as disbonds or delaminations. Surface flaws such as cracks and micro-cracks can be easily detected on different objects like pressure vessels, cylinders and fringes [310], [550], [681].

Laser profilometry can be effectively employed to inspect and analyze various pipes and tubes in different plant machinery. These include: small bore tubes in heat exchangers, feed-water heaters, steam generators, lube oil coolers; curved or bended pipes in boilers and u-bend exchangers; and, large diameter tubes in reformers tubing, serpentine furnace tubing and nozzles. This method is able to detect discontinuities like crack, creep, pitting, erosion, and corrosion, and to identify failure mechanism such as internal diameter expansion, denting and swelling [408]. A laser scanning system is able to acquire substantial quantities of data in a very short time. For instance, with an automated laser profilometry system, a 15 meters long pipe is inspected in approximately three minutes. Software has been designed that automatically compresses and arranges the data for viewing and analysis [519]. Recent technologies and software are able to differentiate between normal pipe surface features such as seam and girth welds, and to identify the depth and severity of discontinuities like corrosion. Besides, there are laser scanning systems for weld inspection [510].

A Profilometry Tool

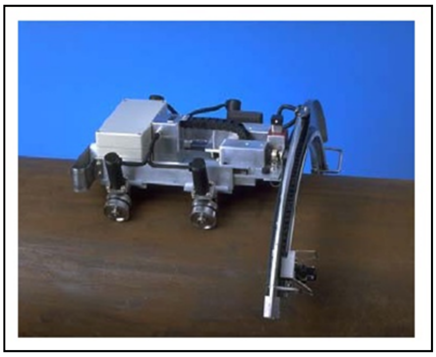


Figure 108 An automated laser scanning tool for establishing corrosion mapping of pipes [510]

Profilometry can also be utilized for inspection of interior of pipelines. One of the approaches is to have a closed circuit television (CCTV) camera fitted on a mobile platform that travels through the pipe recording images onto a videotape. The recorded images are assessed offline by an analyst afterwards. In addition to low quality of the acquired images due to difficult lighting conditions, another drawback of this technique is the exorbitant amount of information generated that can reach about 3 hours of video for inspection of 1 km of pipeline. Laser profilers for pipe inspection have recently overcome the mentioned disadvantages. Automated identification and classification of discontinuities in the internal surface of pipes are also possible by means of artificial neural network systems. This eliminates the potential errors in human based approaches and increases the assessment speed [331], [664].

The applications of laser shearography include serial inspection in the production lines, field inspection in processing and petro-chemical industries, and maintenance and repair of different objects in manufacturing industries. In all applications, the merits of shearography are its fast speed and full field inspection, and high sensitivity even on very complex composite materials. This method scans and views an object's surface and does not penetrate into the material. However, a subsurface defect or discontinuity affects the surface strain field, and therefore, is detectable. Laser shearography is an effective tool in the detection of delaminations, unbonds, disbonds, voids and impact damages in various materials like light metals, laminates, composites, honeycomb structures, and foam insulation. It is also employed to identify internal corrosion, wrinkling, inter-laminar separations, crushed cores, irregular strain concentrations and changes in core splices and bulkheads [566], [584].

Shearograms of an Undamaged and a Defective Cylinder

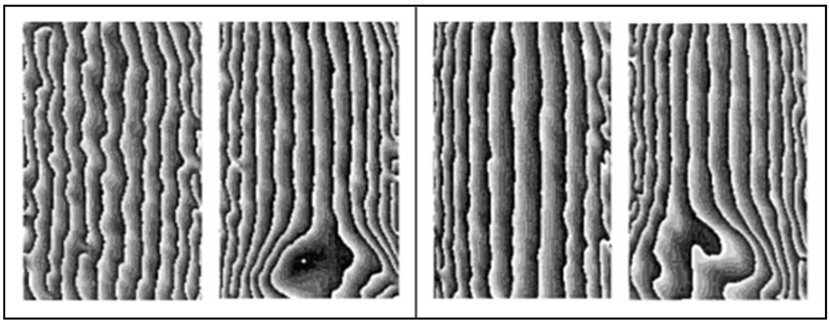


Figure 109 Shearographic investigation of two sintered tungsten-copper cylinders: undamaged specimen and one containing a sintering defect with front sides on the left and back sides on the right [584]

Vibration is a dynamic phenomenon: an oscillatory motion around an equilibrium position. It is caused by energy transfer or storage within structures, resulting from the action of one or more forces. Evidently, this applies by the same token to linear or translational vibrations as well as angular or torsional vibrations. In the latter case, the forcing function is one or more moments instead of linear force acting on the object. Accurate analysis of angular vibration plays an increasingly important role in maintenance and troubleshooting of rotating machinery. Examples of typical symptoms due to angular vibration include: lack of powertrain smoothness and quietness, gearboxes and transmission systems rattle noise, and reduced motor and engine performance.

Laser vibrometry is extremely useful in measuring vibration of rotating parts and small, hot or lightweight objects. It can be utilized for production testing or quality control, vibration measurement through liquids and glass, and when the object is not physically accessible or located in hazardous environment. It is suitable for inspection of fans, ventilators, bearings, gearboxes, transmissions, alternators, cooling systems, compressors, generators, shafts, engines, pumps, electrical motors, washing machines and power tools [163]. The measurements which are carried out by this method are exploited to reduce noise and vibration, study rotational fatigue, improve precision and quality of tool-making machines, monitor and troubleshoot production machinery, and study run-up and run-down of machines. LDVs can be operated on a variety of surfaces. Specular surfaces obey the law: angle of incidence is equal to the angle of reflection. When making measurements on such surfaces, the LDV's optics need to be aligned such that the reflected light returns within the aperture of the collecting optics. Diffuse surfaces scatter the incident light over a large angular area. It is possible to increase the reflection of the surface in the lasers beam direction using retro-reflective tape or paint. This material consists of small glass spheres that scatter light back along the path of the incident beam [492].

Another application of LI is the optical inspection of solder joints in electrical equipment. In fact, due to specularity and complex 3D geometry, the inspection of solder joints has been regarded as one of the most difficult task of quality control and maintenance. Ryu and Cho proposed a new optical solder joint inspection system incorporating laser [532]. In this system, a laser scanning unit scans the area of solder joint and observes the angle of the reflected beam, and statistical pattern recognition method helps classifying the defects of the solder joint under inspection. The defects recognizable with such a system are insufficient and excess soldering conditions.

However, some recent laser inspection systems are able to identify defects like bridges, overhang, high lead and no solder as well. It is notable that in such systems due to the effect of off-specular peaks as the roughness increases, the accuracy of the inspection decreases. In order to achieve more robust results, algorithms which compensate the effect of off-specular peaks must be integrated into the inspection system. As a similar application, in mounting components (e.g. chips) on boards of electric systems, there is always a risk of false mounting which can lead to defect both parts in contact. To eliminate such a risk, 3D laser inspection devices can be utilized that can be automated to meet quality control requirements as well [236].

In order to maintain the accuracy at which an object is fabricated by tool based machining it is necessary to control the dimensions at which the tool operates. This also helps to keep the tool working safe and proper, and to prevent production of defective parts and failure of the tool itself. On-machine optical measurement devices, which use laser to identify the exact dimensions and working path, are currently employed in industry. Such devices do not only inspect the dimensions of the objects being manufactured and the coordinates of the tools' position, but also examine the wear of the machine tools used for the manufacturing processes. This plays a great role in preventive maintenance of machining and drilling tools and spindles [379]. In drilling operations, micro drills are best suited for small hole machining; the condition of operating drill bits have a significant effect on the accuracy of the machining results and failure frequency of the whole machinery. Therefore, micro drills, new or re-sharpened, must be inspected before and during drilling for their exact dimensions and quality conditions. For this purpose, laser microgages (LMGs) can be used to measure the outer diameter of micro drills and the degree of run-out and taper [125], [281].

Basically, laser microgage systems have two key components, a laser transmitter and a digital receiver. The laser housing is machined with a flat base and sides and a variety of mounting points. A highly collimated laser beam is projected from the end of the laser housing and is parallel to the base and sides of the housing. An electronic receiver picks up the laser beam and provides a digital readout showing the height and lateral position of the laser beam. If the laser transmitter and receiver are resting on a flat surface, the display will read zero. If the transmitter or the receiver is then raised off the surface, the differential position will then be displayed. Other applications of laser microgage systems include: measuring stage and table run-out, aligning rolls and web systems, checking gantry and bridge assemblies, aligning lathes and spindle equipment, checking milling and machining equipment, squaring machine tools and actuators, geometric alignment, aligning shafts and gearbox assemblies, plus aligning machinery and equipment mounts [577].

Laser Microgage System

Figure 110 A laser microgage system consisted of a LMG transmitter and receiver plus a digital processor [WS77]

One of the applications of LI is in preventive maintenance of reconfigurable manufacturing systems (RMSs) which are originally designed to economically produce products at high volume and to quickly accommodate changes in product designs and product demand within a family of parts [338]. RMSs are modular in structure, and lodge change through the rearrangement of modules into different configurations. A typical operating scenario for such a system is to produce one or more products for several months and then be reconfigured so it can manufacture different products from the same group of parts. When an RMS is reconfigured, even though intentionally designed for such changes, it is probable to have problems in operation as the result of reconfiguration process.

To illustrate, with each module that is rearranged in the system, there are new opportunities for misalignments and subsequent dimensional errors. Such problems give rise to system down time and slow the process of ramping-up to full production after reconfiguration [42]. Development and growing of noncontact laser inspection capabilities have made rapid inspection of RMSs possible. Laser sensors swiftly generate large amount of accurate noncontact measurements, the acquisition speed and processing accuracy of which open the path for in-process inspection that dramatically decrease the number of failures of such systems [77]. Indeed, one of the challenging tasks in assembly of machinery is the dimensional inspection of the gaps between the main structure and various components to be mounted on it. The employment of an automatic gap-measuring system significantly reduces the costs associated with potential defects due to wrong gap measurements and improper installations. However, nowadays this task is usually performed by humans whose work can always have some degree of error.

These include the mechanical methods which utilize a deformable probe that is fitted into the gap and measure its width or flush, the ultrasonic methods which identify a gap's width by measuring the time required for a high frequency signal to propagate across it, and the electrical methods that find the gap width by measuring the electrical characteristics of the gap such as capacitance. In fact, most of these methods are quite time consuming and provide low precision and subjective results; hence, they are not appropriate for on-line inspections. This is where laser-based optical inspections can be extremely helpful. Such inspections can be executed very fast with no human interface, and with high accuracy of measurement and no risk of damaging.

One of the laser-based instruments which can effectively be used in industry is trummeter. Trummeter is an electronic precision instrument for measuring belt tension as a properly tensioned belt and precisely aligned pulleys grant the longest life time and optimal power transmission of belt drive systems. The instrument has a measuring probe and a microcomputer which are used for measuring the belt tension, calculating the strand force, and checking the rated bearing load of a belt drive. The belt tension can be represented by the belt frequency with the dimension of Hertz. The belt frequency must be measured having the drive off and stationary. The fitted and taut drive belt is tapped in order to make it oscillated with its natural frequency, which is then measured by the probe with the aid of pulsed light. The measured values are displayed in Hertz [Hz]. The measured frequency, the belt mass and the belt length can be plugged in the microcomputer to calculate the strand force. The computed force is then compared with the value provided by the drive manufacturer or a reference value computed at optimal condition. The computed strand force is displayed in either Newton [N] or pound-force [lbf].

A Trummeter in Use

Figure 111 A trummeter used to precisely measure and correct belt tension on a motionless belt [WS48]

The measurement process with a trummeter is quite easy. First the operator has to turn the instrument on and tap the drive belt in order to let it oscillate with its natural frequency. Then he shall hold the measurement probe nearly at the middle of the free strand length at a distance between 3 to 20 mm on top of the drive belt. The successful measurement is denoted by an acoustic signal and the message 'Measurement' which appears on the instrument's display. If the instrument does not provide any results despite careful preparations, this may be due to oscillation of the drive belt below the minimum measurement limit of 10 Hz or insufficient reflection of the light from measuring probe. For the first, the operator must tighten the belt or, if the strand length is very long and open, support the belt in order to shorten the strand length. For the second, a piece of light-colored adhesive tape can be affixed to the belt or the belt can be slightly moistened at the measuring point.

Another instrument that incorporates laser technology is a camera with a CO_2 laser that scans the field of vision and displays it on a monitor as a black and white image identifying sulfur hexafluoride (SF_6) leakage. SF_6 is an inert gas that cannot be seen at room temperature and pressure, and unlike other gases, no chemical can be used to interact with it to make it visible. It is also a very potent greenhouse gas which is emitted in far smaller quantities than CO_2, but with a considerably more harmful effect. Identifying leaks from SF_6 insulated or containing electrical equipment in switch-rooms and switch-yards is associated with some difficulties and critical issues for facility and environmental managers. The gas is also used in electrical power, magnesium production and semi-conductor manufacturing industries.

A CO_2 Laser Camera for SF_6 Leak Detection

Figure 112 A carbon-dioxide laser camera for identification of hexafluoride gas leaks [WS101]

Conventionally, the hands-on methods have been used, with the operator reaching to the equipment to use soaping or sniffing leak testing techniques. This is usually costly and even after the inspection the precise leak source may not be found. Using the CO_2 laser camera, the SF_6 gas leak appears as a wispy black plume. In fact, this technique generates an infrared image of the area under inspection using backscattered laser light at a laser wavelength that is strongly absorbed by SF_6, in the same way that backscattered sunlight produces an image for a conventional camera. The detector in the laser camera is filtered so that it responds primarily to the wavelength of the laser light and ignores essentially all of the background thermal emission. The result is that the invisible gas becomes visible on the display. The key advantage is that it can be used to inspect inaccessible electrical components in operation for possible leaks from a safe distance up to 30 meters away from the individual components. Besides, a permanent video record can be kept for review and future reference [423].

SF_6 Leaks on Gas Circuit Breakers

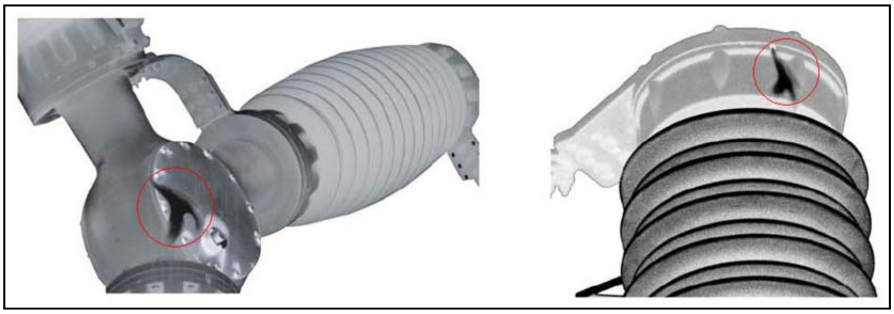


Figure 113 Hexafluoride gas leaks on circuit breakers as shown by a carbon-dioxide laser camera [WS101]

6.5.4 Limitations and Pros

The importance of having any two rotating elements connected across a coupling aligned within tight tolerances has always been an important installation and maintenance issue. With increases in production and machinery speeds, precision alignment has become crucial to machinery condition. Undertaking laser inspection to identify and correct any misalignment has various benefits, which include: reducing unscheduled downtime, increasing profits by minimizing repair costs, improving machinery efficiency and lifespan, enhancing plant safety by reducing the risk of sheared shafts and couplings, cutting energy consumption costs by up to 20% which easily pay back the initial investment, diminishing bearing, coupling, shaft, and seal wear and failures, trimming vibration and noise levels down, and reducing spares inventory levels. With use of the modern laser alignment systems, the alignment time can be drastically reduced which results in faster maintenance, and thus, increased availability of the equipment.

Perfectly aligned machinery directly contributes to the environment. It has been widely appreciated that reduced energy requirements diminish the need for oil, coal and gas. But on top of that, for each day that the service life of shafts, bearings, and other wear components is extended, the manufacture of that spare part is probably delayed. If over a long period, a company halves the use of replacement parts it also reduces the energy and raw material consumption required to manufacture those parts. The shipping requirement of the unmanufactured replacement parts is also eliminated which is a considerable saving. If a company is a manufacturer of such parts, it gets benefit of correct alignment by reducing the number of defective work pieces due to misaligned tools. Abolishing misalignment in such a company does not just increase the availability of machines, but it also reduces the amount of raw materials used and extends the service life of the tools.

The advantages of holographic interferometry include its fast procedure, high resolution graphical representation, simple data conversion and efficient instrumentation. It also enables controlling some imaging parameters such as focus, size and resolution. However, a small unintentional movement or vibration of the specimen can result in a false image. Besides, there is no standard for the distance between the specimen and the holography device; thus, the operator shall be experienced enough to capture the images with the required quality. Laser profilometry distinguishes itself through its flexibility and ability to be easily automated. Laser profilometers, as opposed to tactile profilers, undertake their measurements with in non-contact and for that reason nonintrusive. They also have a higher measurement speed, which makes them ideal for production environments. On average, the merits of laser profilometry method take in: high accuracy, high resolution, and easy data interpretation. In addition, this non-contact method is not affected by exterior attachments to the specimen such as fins and it requires no couplant (e.g. water or gel). The only potential disadvantage is that for extreme high resolution results, the specimen’s surface needs to be clean.

Laser shearography has been progressively used in different industries as its rival methods like ultrasonic and radiography are rather time consuming. Indeed, due to recent development of advanced electronics and lasers, shearography is now a technique for in field nonintrusive testing. The advantages with shearography are that it is a non-contact, full-field technique (i.e. no point measuring, whole area is covered in one single inspection), which can perform fast inspections with high resolution and does not require complex and expensive multi-axis terrain following and probe alignment equipment. It is an operator-friendly method which can cope with a wide range of surface shapes and colors. For example, highly complex compound curved surfaces do not present problems [241]. Besides, the laser shearography instruments are sealed against dust and moisture which allow greater access into different structures and problem-free inspection in various industrial environments. These instruments usually incorporate multiple low power laser diodes with lower safety classification, and hence, permit safe operations.

Coming to the laser vibrometry, it provides high quality images with extremely high spatial resolution within expanded RPM range in an astonishing scanning speed of up to 10 cm per second. Laser doppler vibrometers can be easily integrated and used in production and processing industries and undergo very low level of drop-out noise or ambient vibration in any measurement which ensures high reliability. The operators can quickly setup LDVs and utilize them with a standoff distance between 0.5 and 300 cm that allows fast and convenient repositioning of the laser probe.

Nevertheless, such a setup has high optical sensitivity, and enables accurate measurement of machines' vibration at several locations and in various operating environment. Plus, no adapter, flange or added inertial mass is required for making measurements, leaving the specimen under inspection unaffected. Most of the LDVs in the market ensure eye-safe operation with use of class-2 lasers and are compatible with all standard data acquisition systems. Moreover, recent integration of advanced, miniaturized, optical mirror systems together with the laser source in many vibrometers provides automated scanning, via which a high number of target points can be measured successively [48].

Table 27 Synopsis of laser inspection

Pros	▪ Portable ▪ Fast results ▪ No consumables ▪ Full-field view is possible ▪ No serious safety hazard ▪ Non-contacting measurement ▪ Real time measurement is possible ▪ Sensitive to very small discontinuities ▪ Effective for series or production inspection ▪ Accurate and permanent test record obtained	
Limitations	▪ Safety considerations ▪ Some skills and training required ▪ Subjective interpretation of results ▪ Advance data analysis may be required for precise locating of internal defects	
Equipment	▪ LI equipment and devices vary according to the method of inspection and their applications on different machinery and material. An instrument can be a laser transceiver used for machinery alignment or a large shearographic system for material surface inspection.	
Discontinuity types	▪ Void ▪ Crack ▪ Creep ▪ Pitting ▪ Erosion ▪ Unbond	▪ Disbond ▪ Corrosion ▪ Delamination ▪ Impact damage ▪ Surface-breaking ▪ Rotational fatigue
Discontinuities size	▪ Many recent LI technologies are able to identify discontinuities at scale of microns or even less.	
Relative inspection cost	▪ Required man power costs are relative low; however equipment costs vary according to the LI method and application purpose. A simple trummeter can be purchased between 300 € and 600 €, and a laser shaft alignment kit may cost up to 8,000 € depending on its complexity and functionality.	

6.6 Leak Testing

Leak testing (LT), also known as leak detection, is one of the NDT techniques, which is concerned with the escape of fluids (i.e. liquids and gases) or vacuum from sealed machinery components or systems. As early as 1986, Marr expressed the great impacts of leak detection on the safety or performance of sealed products [407]. Nevertheless, LT methods are not exclusively used to test the manufactured products but are finding increasing applications in maintenance of various industrial machinery and equipment. Accordingly, leak definition is evolving to accommodate the industry point of view: a leak always requires a flow of mass though the walls of a volume intended to be sealed [202]. Reliable leak testing saves costs by reducing the number of major failures coupled with leakages and their production-related and environment-associated consequences.

6.6.1 Conception

Fonseca et al. describe a leak as an unwanted path through an enclosure or a wall [202]. Indeed, this description is also used in the absence of a pressure difference if it is expected that the concentration in each side of the enclosure or wall is constant. However, the leak rate is defined as the throughput of fluid through a leak which is indeed a function of its type, pressure difference and temperature. It is possible to categorize leaks based on the nature of the material or joining fault. For instance, leaks are very often due to welding defects or other permanent joining means, O-rings and other sealing elements are also common leak sources; porosity and materials defects can be considered as another category of leaks too. Besides, although most leaks may be found in both vacuum and pressurized systems, some of them are typical for one type of system. For example, leaks due to porosity are more typical to appear in the pressurized system owed to very high-pressure difference, while virtual leaks (i.e. leaks that cannot be identified by leak detectors from outside a system under inspection) are more common in vacuum systems.

Table 28 Commonly used units for leak rates and their conversion factors [354]

Unit	cm^3/s*	Torr.l/s	Pa.m^3/s	mbar.l/s
cm^3/s*	1.00	0.76	0.10	1.01
Torr.l/s	1.32	1.00	0.13	1.33
Pa.m^3/s	10.10	7.50	1.00	10.00
mbar.l/s	0.99	0.75	0.10	1.00
* Under standard temperature and pressure (0 °C and 1 atm) also shown as std.cm^3/s; e.g. 1x10^{-4} std.cm^3/s is equal to loss of 1 cm^3 of air over 3 hours.				

To more precisely explain, leaks may come out by a range of defects within the material and/or at connecting areas: at fixed connections by brazing, welding or gluing (especially at transitions between different materials like glass-metal, ceramics-metal, etc.); at pores and hair cracks due to mechanical or thermal stress, which to some extend are always present and therefore must be small enough in size and number such that they do not disturb; and at flanged connections. There exist also cold and warm leaks opening up at extreme temperatures and often being reversible; virtual leaks, where gas is evaporating from inner excavations, dead holes etc.; and, indirect leaks from supply lines for (e.g. cooling water or gas/liquids like helium and nitrogen) of cryogenic systems. And lastly, a leakage, but not a leak due to a defect, is permeation which is the natural porosity of material. Permeation could be quite significant and even limit the detectable leak rate in some cases [680].

On the whole, one may consider that the external leaks are the results of poor welds or poor usage of seals that created path between the inside and outside of a system while virtual leaks are usually resultants of manufacturing defects within the material or a lack of complying with good vacuum practice. To identify and measure leaks there are a wide range of methods and instruments intaking a variety of simple to sophisticated technologies depending on the machinery parts or object to be inspected [21]. Of course, it is central to choose a leak detection method that satisfies the required levels of sensitivity and speed in addition to no being more complicated and expensive than necessary. The major leak testing methods can be listed as: Bubble emission leak testing (BELT), chemical reaction leak testing (CRLT), gas detection leak testing (GDLT), halogen diode leak testing (HDLT), hydrostatic leak testing (HSLT), pressure change leak testing (PCLT), radioisotope leak testing (RILT), tracer gas leak testing (TGLT), and vacuum flow leak testing (VFLT).

1. *Bubble Emission Leak Testing:* BELT, also known as bubble test, is the most common method of leak detection in industry. The concept of bubble testing consists of pressurizing an object, placing it in water bath and looking if there is a brook of bubbles coming out of the object or not. Such a test can also be undertaken by applying a soap or bubble forming solution to the part being tested. Bubble leak testing is more qualitative rather than being quantitative; while small leaks generate numerous small bubbles, it is not easy to estimate the actual leak rate [438]. It is important to consider that in BELT via immersion oils are more sensitive than water; plus, when testing by reducing the pressure above the liquid (e.g. in testing a pressure vessel) several precautions have to be taken into account, especially if the reduced pressure brings the liquid close to its boiling point. If the liquid begins to boil, a false leak indication can be observed. Besides, the test object has to be carefully cleaned to increase surface wetting in order to avert bubbles from clinging to its surface and to avoid contamination of the fluid. In case water is used it should be distilled or deionized and handled with minimal sloshing to trim down the absorbed-gas content. Usually, some amount of wetting agent is added to the water to decrease the surface tension and increase its sensitivity. Bubble forming solutions can also be used for the objects which are too large or unmanageable to submerge. However, care must be taken to ensure that no bubbles are produced by the process itself [80].


Bubble Emission Leak Testing

Figure 114 BELT using various bubble-forming solutions on different machinery elements [WS8], [WS35]

2. *Chemical Reaction Leak Testing:* CRLTs are based on the detection of gas escape from inside a pressurized object such as a vessel, tank or a valve by means of sensitive liquids or gases. Among all the existing techniques, five are commonly used in industry. First is the ammonia color change technique in which the surface of the specimen is cleaned and then a calorimetric developer is applied on the surface where it forms an elastic film that is easily removed after the test. The developer is fairly fluid and when sprayed, it sets quickly and adheres to metal surfaces forming a continuous coating. Then, an air-ammonia mixture (i.e. 1% to 5% NH_3) is injected into the specimen. Leakages of this mixture through the discontinuities cause the film to change color and indicate the leak spots. The sensitivity of this technique can be controlled by changing the ammonia concentration, the pressure applied to the air-ammonia mixture and the time allowed for the development. Second is the indicator tape technique which is particularly used to test welded joints. In this technique, after cleaning the joint surface with a solvent, the indicator tape is fixed on the weld either by a rubber solution applied on the edge of the tape or by a plastic film. Then the inspection gas which is usually an air-ammonia mixture (i.e. up to 10% NH_3) is fed into the object at excess pressure. If any discontinuity exists, the gas seeps and reacts chemically with the indicator, resulting in colored spots that are clearly visible on the tape. Third is the ammonia and hydrochloric acid reaction technique which involves pressurizing the test object with ammonia gas and then search for a leak with an open bottle of hydrochloric acid. A leak generates white mist of ammonium chloride as ammonia comes into contact with the hydrogen chloride vapor. Fourth is the ammonia and sulfur dioxide reaction technique which is indeed a modification of the previous technique. It involves the reaction of the ammonia and sulfur dioxide gas generating the white mist of ammonium sulfide. Last of all is the halide torch technique. The torch consists of a gas (fuel) tank and a brass plate. Burning gas heats the brass plate and forms a flame which changes color in the presence of halogen gas because of the generation of copper halide [80]. Recently, with the availability of more modern techniques, CRLT techniques have been employed less frequently in industry.

3. *Gas Detection Leak Testing:* GDLT involves using detectors to identify leakage of a wide range of gases. The detectors, utilizing various techniques and technologies, are made as fixed or handheld equipment, some of which are able to measure the leak rate or their qualitative severity in addition to the main detection task. The gases which can be identified by industrial GDLT detectors are: Oxygen (O_2), ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), hydrogen cyanide (HCN), nitrogen dioxide (NO_2), ammonia (NH_3), chlorine (Cl_2), chlorine dioxide (ClO_2), phosgene ($COCl_2$), phosphine or phosphorus trihydride (PH_3), methane (CH_4), propane (C_3H_8), and butane (C_4H_{10}). Due to the low cost and robustness, GDLT is one of the most commonly used LT methods in industry.

Handheld GDLT Leak Detectors

Figure 115 From left to right: a combustible gas leak detector [WS16], a carbon monoxide leak detector [WS96], a multi-gas leak detector enables to simultaneously identify five different gases using changeable sensors [WS65]

4. *Halogen Diode Leak Testing:* In HDLT a leak detector is used that responds to most refrigerant gases containing very active and nonmetallic elements: astatine, bromine, chlorine, fluorine or iodine. The detector is able to identify leakage of these halogen-rich gases in the systems working with them or such gases can be used as a tracer gas for leak detection in other specimens. The halogen concentration, type of halogen gas (that is being used (i.e. as a tracer gas) or sought, and the differential test pressure are the three major factors affecting the sensitivity of HDLT. The sensing element of the leak detector operates on the principle of ion emission from a hot plate to a collector.

In fact, the rate at which positive ions are generated id proportional to the halogen concentration of the gas passing through the detector. Generally, the HDLT detector's sensor is potentially more sensitive than the halide torch, halide sensitive tape or halide sensitive paint sensors. Standard leaks of known size are used for calibration of halogen diode leak detectors. All of the halogen leak detectors have a control unit and a probe through which air is drawn. When looking for leaks from an enclosure pressurized with a tracer gas, the probe tip is moved over joints and seams suspected of leakage. It is important to keep in mind that the probe tip should lightly touch the surface of the inspected object as it is moved; plus, where forced ventilation is required to keep the air free of halogen vapors, it must be stopped during the test or care must be taken to ensure that drafts do not blow the leaking gas away from the detector's probe. As the probe passes over or gets close to a leak, the gas is drawn-in with air and through a sensitive element where it is detected; and just right after, an audible or visual signal is generated [80], [438].

Handheld and Portable HDLT Leak Detectors

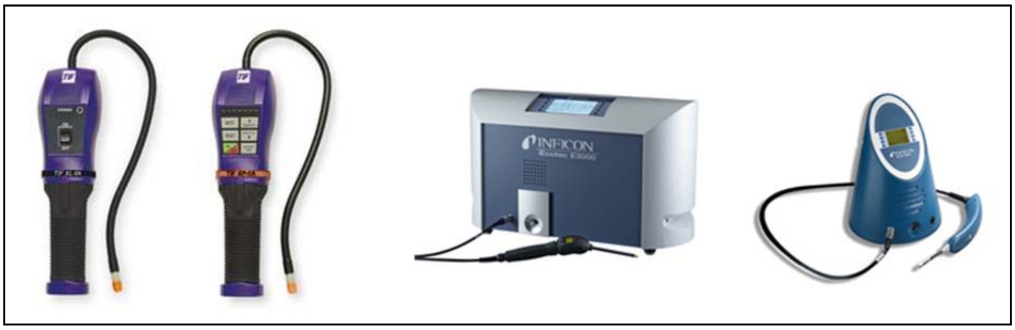


Figure 116 Various handheld and portable HDLT leak detectors [WS52], [WS95]

5. *Hydrostatic Leak Testing:* HSLT require that a specimen is entirely filled with a liquid such as water; pressure is slowly applied to the liquid until the required pressure is reached; then, it is held for the required time at which point visual inspections on the specimen are undertaken. Such a test has not very high sensitivity and thus only large discontinuities can be identified by this method. However, the sensitivity of this test can be enhanced by either application of a developer to the outer surface of the specimen that changes color when contacted by small water leaks, or use of special solutions that decrease the surface tension of water and provide a visible or fluorescent tracer. HSLT can be used on piping, tanks, valves and containers with welded or fitted sections.

6. *Pressure Change Leak Testing:* PCLTs are undertaken to determine the existence and rate of possible leaks. The concept of pressure change method is based on the fact that a leak inherently causes a pressure change in a closed volume. By knowing the volume and pressure of the pressurized system, and ability to record leak-related pressure changes in time, a relatively precise measure of leak rate can be achieved [438]. In such a case, the initial pressure may be above or below the atmospheric pressure thus leading to pressure drop or pressure rise. For an expected pressure rise leakage, the object is evacuated to the testing pressure, which has been selected so that in particular time interval the pressure remains constant in the absence of very short leaks. Of course, this holds when outgassing (i.e. releasing some gas molecules that were captured during an absorption period by a material taken place when exposed to atmospheric pressure) from the walls is negligible and the test pressure is above the vapor pressure of the object's material. For most dry materials, pressure above 1 millibar satisfies this requirement providing transient times bellow 1 second. Then the test object is isolated from the pumping system and the pressure is monitored as function of the time. If a leak is present, a linear increase of the pressure will be observed (i.e. for small pressure changes); conversely, the absence of leaks results a constant pressure. For an expected pressure drop leakage, a similar leak testing method is applicable: the object is pressurized and the pressure is monitored as function of time where the absence of leaks leads to observation of no pressure deviation. If the testing pressure is not much higher than 1 bar, then this method can also be used for vacuum components. It is essential to highlight that although higher test pressure results in higher test sensitivity, but very high test pressure is harmful for many machinery components and equipment. Another important factor is that in testing large objects such as large tanks or containers and in long test periods, effects of temperature changes have to be considered as well [202].

7. *Radioisotope Leak Testing:* RILT entails use of fluid solutions containing radioisotopes as radioactive tracers. As Mix utters, radioisotopes with sort life can be employed to identify leaks through hermetically sealed cavities and closed piping [202]. In such a test, water is the liquid most commonly used, although in particular industries like petroleum, hydrocarbons are extensively employed instead. In gas systems, a radioactive tracer gas can be added to the system and tracked through. The process path and flow rate can be determined by placing detectors downstream of the injection point and measuring the injection-to-detection time. The unexpected loss of flow or the detection of the tracer gas at an unexpected location can denotes a leak. In liquid systems, soluble salts and compounds containing radioisotopes are added to the liquid. For example, radioactive barium tracers can be included to some process liquids and similarly tracked.

   Another isotope which can be added to liquids, especially water, is the sodium isotope ^{24}Na. The use of sodium isotope is safe as the required concentration for leak detection is less than drinking tolerance. In addition, ^{24}Na has a short half-life of only 15 hours and can be kept in the system until its activity has been greatly decreased due to radioactive decay. Using sodium isotope, the test object is filled is filled with sodium bicarbonate solution and pressurized to the level set by the test standards. After a short time, the test object is drained and flushed with fresh water. Then a gamma radiation detector is employed to identify the location of leaks from the presence of gamma radiation emitted from the radioactive bicarbonate solution that has accumulated around the leaks [80]. In general, RILT has sensitivity as high as helium mass spectrometry but it is more expensive and sometimes the radiation safety regulations limit its applicability in industry.

8. *Tracer Gas Leak Testing:* TGLT involves using tracer gases like oxygen and carbon dioxide for seal and package inspection [11], and helium, hydrogen and sulfur hexafluoride for inspection of machinery objects. In fact for industrial applications, Zapfe explains that a tracer gas should have unambiguous signal in the mass spectrum of the residual gas and also very low content in air [680]. Plus, it has to be chemically and physically inert, non-explosive and cheap in addition to easily removable by pumping and not contaminating the test system. Helium and hydrogen both satisfy all of these requirements. Each of these gases has got advantages and drawbacks which have to be taken into account before selection. Hydrogen has a much higher molecular velocity, and thus, it diffuses rapidly inside test objects, and dissipates far more quickly than helium. Additionally, it can be usually purchased at lower prices. However, despite some technological advancement, there are not many suitable detectors in the market; and, the risk of its flammability is usually available. Therefore, helium is still the more commonly used tracer gas for leak detection in industry; although, the increasing use of hydrogen as a tracer gas is not also negligible.

   Basically, there are three major ways of undertaking tracer gas leak testing: spraying, global measuring and sniffing; the first of two are the most sensitive leak detection techniques. The spraying method involves testing a vacuum object or an air-filled object, whose air is being pumped out, by spraying a tracer gas on its surface and measuring its flow into a detector connected to the object. The global measuring can also be used for pressurized (pressure-envelope technique) or vacuum systems (vacuum-envelope technique). A specimen is placed in a test chamber and it is then pressurized by a tracer gas which seeps from leaks and detected by a detector connected to the chamber. Or, the tracer gas source is connected to the chamber and the detector to the specimen (i.e. identifying the gas penetration) if it is a vacuum object. The sniffing technique is realized by pressurizing a specimen and searching for potential leaks around it outer surface by a leak detector [202], [501].

Spraying, Global Measuring and Sniffing TGLT Methods

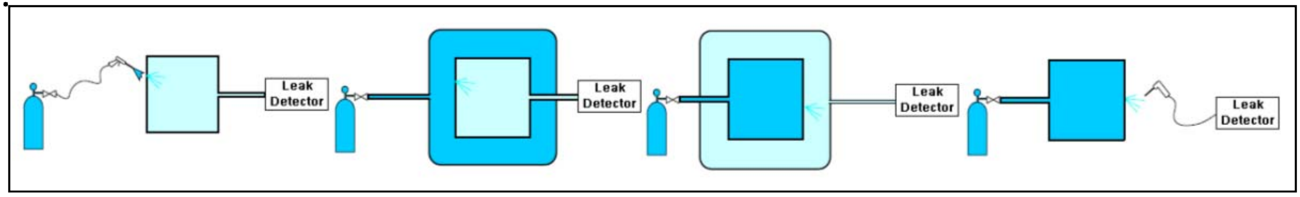


Figure 117 A schematic showing different TGLT methods; from left to right: spraying, global measuring (for pressurized and vacuum objects) and sniffing [680]

9. *Vacuum Flow Leak Testing:* VFLT, although using a tracer gas, is categorized as a separate leak testing method due to the techniques and configurations employed and also its applicability (i.e. being utilized only to test vacuum systems). There exist two major techniques realizing a VFLT. First is the direct or conventional flow technique, in which a leak detector (i.e. having a spectrometer) is connected to a vacuum system such that the tracer gas is flowing wholly or partially through the detection cell. In this technique, both the leak detection cell and pumps are directly connected to the vacuum system. The ratio between the partial pressure increase in the leak detection cell and the tracer gas flow (usually helium) through the leak defines the intrinsic sensitivity of a leak detector. To raise the sensitivity, pumping speed for the tracer gas has to be reduced without decreasing the pumping speed for the other gases. Alternatively, as Zapfe asserts, to increase the sensitivity in such a system, a throttle valve can be installed to reduce the gas flow into the pumps [680]. The early systems had diffusion pumps used to generate high vacuum, and also liquid nitrogen traps to prevent the migration of diffusion pump fluid to the test object. However, operation of such a system had many difficulties. The cold trap needed to be refilled periodically during operation requiring an easy access to a liquid nitrogen source. The diffusion pumps had to be operated in quite well defined ways as they were susceptible to mishandling such as inadequate venting. For that reason, turbo-molecular or turbo-drag pumps started to replace the diffusion pumps and cold traps [272], [438].

   Second, is the reverse or counter flow technique, in which the leak detector is connected to the inlet of a high-vacuum pump instead of the direct connection to the vacuum system. The technique takes the advantage of the fact that the compression ratio of turbo pumps increases rapidly with the mass of the pumped gas. Thus, by injecting the gas from the test object at the exhaust of the pump it is possible to get at its inlet a back-streaming flux largely enriched for lighter gases. However, a major shortcoming is the direct connection of the vacuum system to the roughing pump and consequently the risk of its contamination by oil vapor. The stability of the pumping characteristics is also important to ensure the necessary stability for accurate leak detection. The low pumping speed of the roughing pump increases significantly the time constant for leak detection. Nonetheless, installing a second turbo-molecular pump between the vacuum system and the roughing pump provides clean pumping while maintaining high pumping speed. Nowadays two stage turbo-molecular pumps are most widely used having an outlet flange between the two stages to the leak detection cell. Alternatively a simple counter flow leak detector can be connected to the outlet of the turbo-molecular pump in a pump station. With the recent developments of dry pumps, more and more counter flow leak detectors using dry pumps are available in the market, thus avoiding contaminations from oil vapor [680]. Moreover, the counter flow detectors offer several advantages in comparison with the direct flow detectors. They eliminate the need for cold traps, or as the tracer gas is no longer flowing directly through the detection cell (i.e. just a part of it by back-streaming through the high-vacuum pump) the pressure in the cell is lower and consequently the detection can start earlier. In addition, the leak detection cell and thus the filament are better protected in case of a sudden pressure increase. On the whole, although the direct flow technique is quite fast and very sensitive but the counter flow technique has been used more in industrial vacuum leak detections due to its mentioned advantages except for the detection of very fine leaks [116], [354].

Conventional and Counter Flow VFLT Methods

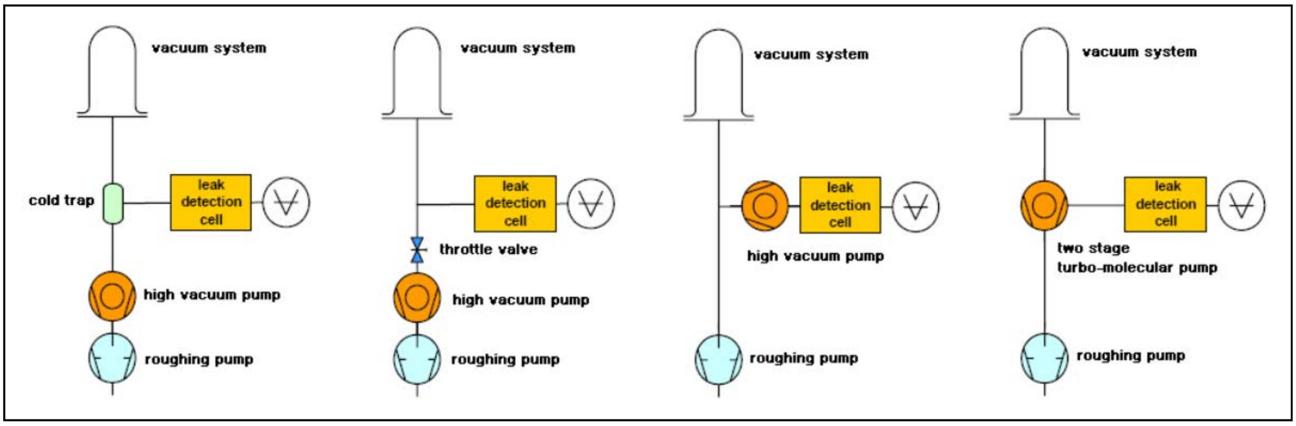


Figure 118 A schematic showing different VFLT methods; from left to right: conventional flow with a cold trap and a throttle valve, and counter flow with a single stage high-vacuum and two stage turbo-molecular pumps [680]

The turbulent flow of a pressurized gas through a leak generated sound of both sonic and ultrasonic frequencies. Sonic emissions are detected with proper equipment (e.g. a microphone); though, an adequately large leak can probably be identified with the ear. Smaller leaks can be detected with ultrasonic probes operating in the range of 35 to 40 kHz. Ultrasonic detectors are so sensitive that they are capable of identifying an air leak from 15 m distance through a 0.25 mm diameter hole at 35 kPa pressure. It is essential to note that the generated sound level is an inverse function of the molecular weight of the leaking gas which means a given flow rate of a gas such as helium generates more sound energy than the same flow rate of a heavier gas such as nitrogen or air [80].

Another nondestructive test which can be practically adapted for leak testing is thermographic inspection or simply thermography. This method is particularly useful when the object and expected leak(s) are large enough to be detected in addition to having a measurable temperature differential between the two mediums (i.e. the leaking system and the containing system). Today, leak testing by thermographic inspection is commonly used in manufacturing and processing industries.

Penetrant testing can also be utilized as an economical leak testing method. Special dyes can be sprayed on high-pressure side of suspected leak areas. If there is a leak, the differential pressure of the system will cause the dye to seep through the leak and appear on the low-pressure side of the object under inspection. The use of visible liquid penetrants for leak testing is only slightly limited by the configuration of the object under inspection. In addition, it is equally suited to ferrous, nonferrous, and nonmetallic materials provided that they are not adversely affected by the application of the penetrant used. However, penetrant testing can take an hour more for average test sensitivity; because of such long testing time, leak testing using penetrants are not widely used in industry [438]. More to these points can be read through the sections of ultrasonic testing (UT), thermographic inspection (TI), and penetrant testing (PT).

6.6.2 Tools and Techniques

As explained before, leak testing defined in its simplest form is a division of nondestructive testing employed for the detection (i.e. location identification or rate measurement) of fluid leakage in either a pressurized or an evacuated system. It is essential to keep in mind that the word 'leak' refers to a physical opening and not to quantity of gas or liquid flowing through the opening. Therefore, leaks are flaws that distress safety or performance of a system or give rise to environmental contamination or energy loss. The term 'leakage' refers to the flow of a fluid through a leak without regard to the physical size of the opening. Characteristically, leakages take place as a result of pressure difference across the opening; nevertheless, capillary effects can also be a reason for leakage. The fluid flow rate across an opening is associated with the geometry of the leak, the nature of the leaking fluid and the prevailing pressure and temperature. In fact, nothing can ever be totally free of leakage even so minute. There are various tools and techniques which are incorporated in leak testing; the selection of the proper ones is associated with two major issues: the required leak tightness according to the standards for a given object and the way this standard can be met most economically and reliably [25].

There exist a large number of leak testing tools and techniques where each has its own sensitivity range, advantages and disadvantages. Of course, not all tools and techniques are useful for every application. By using a number of selection criteria, the choice can often be narrowed to two or three techniques with the final choice being determined by special circumstances or cost effectiveness. The first criterion is the intention of the test. For example, if it is to locate every leak of a certain size (i.e. if the specimen is valuable and repairable), or, if it is to measure the total leakage from the specimen without regard to leak number or location (i.e. inexpensive objects are often not worth the reworking cost and a simple accept-reject criterion is adequate).

The second criterion is whether the test object is under pressure or vacuum. Many techniques are reliably useful only for one of these cases. Besides, there are other selection criteria which can be applied to narrow the field more. For instance, if the specimen already has a useable tracer gas incorporated in it (e.g. ammonia in some systems), one technique may be preferably chosen. Other criteria may involve the sheer size of the specimen (i.e. for pressurizing techniques) and the time factor. Taking into account all of the crucial criteria for a particular case, the most appropriate tools and techniques are to be selected [26].

In BELT immersion test, the part under test is internally pressurized, submerged in a liquid, (i.e. typically water) for a period of time, and then the operator examines it for bubbles. In fact, water-immersion BELT has proven to be an insensitive method but water with additives has shown to be one of the most reliable ways to locate leaks. By controlling pressure and the concentration of additives the immediately discernible leak rate can be changed. Bubbles form at the source of the leak as a result of air pressure, and the amount of bubbles per minute can signify the size of the leak. While the initial cost of a BELT tank is low, in practice it is expensive primarily as the water becomes contaminated (i.e. with dust, oil, lubricant, residual metal parts and etc. on the test object), thus producing a hazardous waste requiring special disposal. In addition to disposal, maintenance of the water for pH, bacteria and skimming the surface to control skin rashes plays an important role. On the other hand, it is possible to have a thin film of a special liquid or solution(s) on a pressurized system. In this technique, an internally pressurized specimen is covered with such a liquid/solution film that allows the formation of visually discernable bubbles. As the pressurized gas escapes through the leak, it causes the thin film of liquid on the surface of the object to bubble and thus indicate the leak location [108].

The chemical reaction leak testing is based on detection of gas seepage from inside an object by means of sensitive solutions or gas. It usually includes the application of colorimetric or colormetric developers and commonly employed in different industries. Its use is rapidly expanding for very large objects. The most practical technique is to use ammonia as a tracer gas inside of the test object and a powder developer on the outer surface. This developer react (i.e. changes color) as ammonia traverses the minute leak(s). In CRLT, specific sensitivity rates can be calculated by varying the pressure differential, test time, and ammonia concentration. The test procedure is as follows: First the operator has to make sure that the interior and exterior surfaces (including welds and joints) where leaks are often found are free of oil, grease, flux, slag or other contaminants that might temporarily block or mask leakage. Then, the developer is applied to the weld, joint or surface where leakage is of concern and it is left to become dry. Afterwards, once activating tracer (e.g. ammonia) has been given enough time to infuse the specimen and sufficient dwell time is taken for the tracer to penetrate to the surface treated with developer, the specified color change will take place at the leaks.

Various Colorimetric Developers

Figure 119 A picture showing photos of different colorimetric or colormetric developers used for CRLT [WS8]

In gas detection leak testing, the seepage inspection and finding process is undertaken by use of various detectors which can be in form of fixed sensors near the critical components (which are not easily accessible) or handheld devices used by operators in plant. Today, there exist many sensors capable of detecting various gases and vapors ranges from oxygen and carbon dioxide to a long list of combustible and toxic gases. Some of these detectors do not only alarm the existence of such fluids but also measure the leak rate or provide their quantitative/qualitative harshness. As these gas detectors are quite cheap and easy-to-use, they have been increasingly employed in industry.

Handheld and Stationary GDLT Probes

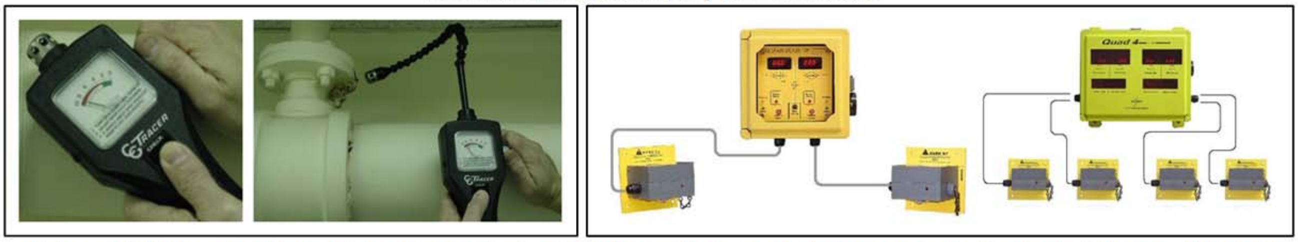


Figure 120 A handheld multi-gas leak detector [WS8], multi-channel stationary toxic-gas leak detectors [WS25]

Table 29 List of combustible and toxic gases or vapors which are currently detectable by various GDLT detectors

Acetaldehyde	Butyl Alcohol	cl,1-Dichloro-1-Nitroethane Cumene	Dimethylamine	Ethyl Bromide
Acetone	Butyl Acetate	Cyclohexane	Dimethylaniline	Ethyl Formate
Acetonitrile	c-Allylglycidylether	Cyclohexanol	Dimethylformamide	Ethyl Benzene
Acetylene Tetrabromide	c-Chloroform	Cyclohexanone	Dimethylhydrazine	Ethyl Alcohol
Alcohol	c-Dichloroethyl Ether	Cyclopentadiene	Dinitrobenzene	Ethyl Chloride
Allyl Alcohol	Camphor	DDT	Dinitroluene	Ethylamine
Ammonia	Carbon Monoxide	Diacetone Alcohol	Dipropylene Glycol Methyl Ether	Ethylene Dichloride
Benzene	Carbon Tetrachloride	Diasomethane	Disobutyl Ketone	Ethylene Oxide
Benzoyl Chloride	Chloro-1-Nitropropane	Diborane	Epichlorhydrin	Ethylenediamine
Benzoyl Peroxide	Chloroacetaldehyde	1,1 Dichloroethane	Ether	Formaledehyde
Butane	Chlorobenzene	1,2 Dichloroethane	Ethoxyethanol	Furfuryl Alcohol
Butanone (MEK)	Chloropicrin	Diethylamine	Ethyl Butyl Ketone	Gasoline
Butoxyethanol	Chloroprene	Diethylamino Ethanol	Ethyl Ether	Glycol Monoethyl Ether
Heptane	L.P. Gas	Methylal	Nitrotoluene	Refrigerant R-11 (Freon 11)
Hexachloroethane	Lacquer Thinners	Methylamine	Pentane	Sulfur Dioxide
Hexane	Methane	Methylchclohexanol	Pentanone	Tetrachloronaphthalene
Hexanone	Methyl Acetylene	Methylcyclohexane	Perchloroethylene	Tetranitromethane
Hydrogen Sulfide	Methyl Cellosolve	Methylene Chloride	Petroleum Distillates	Toluene
Hydrogen Chloride	Methyl Isobutyl Ketone	Naphtha	Phenylether	1,1,1 Trichloroethane
Hydrogen Bromide	Methyl Butyl Ketone	Napthalene	Propane	1,1,2 Trichloroethane
Hydrogen	Methyl Mercaptan	Natural Gas	Propargyl Alcohol	Trichloroethylene
Isoamyl Alcohol	Methyl Chloroform	Nitrobnzene	Propylene Oxide	Trichloronaphthalene
Isobutyl Alcohol	Methyl Alcohol	Nitrochlorobenzene	Propyne	Trichloropropane
Isopropyl Alcohol	Methyl Chloride	Nitroethane	Refrigerant R-502 (Freon 502)	Trinitrotoluene
Isopropyl Glycidel Ether	Methyl n-Amyl Ketone	Nitroglycerin	Refrigerant R-123 (Freon 123)	Turpentine
Ketone	Methyl Ethyl Ketone	Nitromethane	Refrigerant R-22 (Freon 22)	Xylene

Regarding the HDLT, a dynamic test can be undertaken by evacuating the interior of the specimen, while applying a halogen-rich tracer gas to its outer surface and inspecting the evacuated gas with a leak detector probe. On the other hand, a static test is carried out by pressurizing the interior of the specimen with the tracer gas and then sniffing or scanning the outer surface with a leak detector probe. When objects like pipes, vessels and tanks are being prepared for HDLT, care must be taken that they are free of moisture, grease, paint, solvents and dirt that could momentarily cork the leaks. Plus, if specimens are pressurized with a mixture of air and refrigerant, the refrigerant hast to be added in advance so that the air is let to mix and disperse the refrigerant through the specimen [438].

An Advance HDLT Detector

Figure 121 An advance handheld HDLT leak detector which is not only capable of detecting halogen-rich gases but the combustible gases as well [WS16]

Coming to hydrostatic leak testing, it is used to test components for leaks by pressurizing them inside with a liquid which is usually water. HSLT requires that a component be entirely filled with a liquid such as water. Pressure is slowly applied to the liquid until the required pressure is reached. The pressure is kept constant for a required time period after which the component is inspected visually to locate leaks. It is notable that objects under inspection are permitted to have painting and insulation; however, paintings and particularly insulations rise the average normal test time of 6 minutes per centimeter of wall thickness by a factor up to 10. Another important factor to keep in mind is that, if the pressure is increased above the required level, the test fluid may tend to obstruct very small leaks (i.e. $1x10^{-6}$ std.cm^3/s and smaller). Special solutions that decrease the surface tension of water and provide a visible or fluorescent indication can be used to enhance the sensibility of the HSLT.

Liquid Sensitivity Improvers for HSLT

Figure 122 Different liquid sensitivity improvers for HSLT. From left to right: surface tension reducer liquid; water soluble and florescent tracer liquid [WS8]

Pressure change leak testing requires pneumatic pressurizing of a closed object. After isolating it and adjusting for temperature, the initial pressure and the final pressure in the object are compared. If there is leak, it intrinsically causes a pressure change the closed volume. The change in pressure can also be used to calculate the leak rate given the internal volume of the test object. Of course, the initial pressure may be above or below consequently resulting in a pressure drop or pressure rise. A pressure drop or pressure decay test is undertaken for the objects with the initial pressure above the atmospheric pressure and the pressure rise or pressure gain test is run for the specimens at pressures less than atmospheric pressure. PCLT usually necessitates a minimum of one hour and may run several days as the volume of the test object increases. Although theoretically the test sensitivity can be increased by extending the test time, its practical sensitivity is not relatively very high. Besides, with higher test pressure higher test sensitivity is attainable but negative effect of very high pressure on the test object has to be taken into account.

Mentioned above, pressure, temperature and time are the parameters that change during a PCLT. In test with long-duration pressure change, atmospheric or barometric pressure must be measured or compensated for as it tends to vary. In such a case, extending duration of test increases the reliability of the results. On the other hand, for short duration test (i.e. 1-3 hours) it is not usually necessary to consider atmospheric pressure changes. Absolute pressure gages measure any pressure above the zero value that refers to a perfect vacuum. Gauge pressure gages measure any pressure which is zero referenced against ambient air pressure. In large volume systems, they are utilized to measure the test pressure regardless of the atmospheric pressure. Technically, pressure measuring devices may be divided into three groups: those based on measurement of the height of a liquid column such as Bourdon tube, u-tube manometer and mercury manometer, those based on measurement of the distortion of an elastic pressure chamber, and electronic sensing devices [438]. Today, conventional pressure transducers found in industry are of both manometers and the electronic detectors with which the object's pressure is measured and converted electronically to an appropriate current, voltage, or digital output signal. These transducers are typically made from ceramic, silicon, or stainless steel. In last decade, a new generation of electrical sensors with built-in diagnostics capabilities has been developed which are known as smart pressure transducers [416].

Manometers and Electronic Pressure Transducers

Figure 123 Photos of single and dual input manometers [WS97], various electronic pressure transducers [WS81]

As explained in the previous section radioisotope leak testing employs solutions containing radioisotopes as radioactive tracers to identify leaks. In liquid systems, water or hydrocarbons like oil are used as base liquids to which the tracer isotopes are added. In gas systems, a radioactive tracer gas can be added to the system and tracked through. The process path and flow rate can be identified by placing radioisotope detectors downstream of the insertion point and measuring the time to detection. The unexpected loss of flow or the detection of the tracer gas at an unexpected location can denotes existence of leak(s). RILT is a fine LT technique, with better sensitivity than $1x10^{-5}$ std.cm^3/s, which has to be run before application of a gross leak test as any used tracer fluid may plug capillary leak channels, preventing the influx of radioisotopes, and resulting inaccurate fine leak measurement. It is important to note that although RILT provides higher sensitivity than TGLT, it cannot be used to determine the location of leak spot(s). In addition, it is more expensive and entails restrict radiation safety regulations. Therefore, RILT is rarely used in manufacturing and processing industries [435].

Coming to tracer gas leak detection, basically a tracer gas is introduced to one side of a specimen. Then, a differential pressure is applied to the specimen, with the higher pressure at the tracer gas side. An instrument, such as a mass spectrometer, is then applied to the lower-pressure side of the specimen to detect the presence of the tracer gas. The gases used in this technique are typically helium (the most commonly used), hydrogen and refrigerant halides R-12 and R-22. However, the test is not as simple as that; it incorporates various techniques which can be used for a range of applications. These can be divided into vacuum and sniffing techniques or, as another classification, to techniques for leak location or global test. For the purpose of this work the second classification is preferably considered. To determine the location of leak(s), for maintenance and quality control applications, the two used techniques are spraying and sniffing. Spraying, as a vacuum technique, involves removing air from the specimen connected to an analyzer cell and then spraying tracer gas (e.g. Helium) over its outer surface (i.e. where potential leaking areas are located). The detector measures the flow of tracer gas penetrating the specimen and the leak can be located. Spraying technique is used if the system or piece to be tested can be placed under vacuum and if there is a need to detect very small leaks. Sniffing involves pressurizing the specimen with tracer gas and then inspecting its outer surface for possible gas seepages with a long distance sniffer (LDS) probe. Sniffing technique is used if the system or piece to be tested cannot be placed under vacuum and if sensitivity is not a major concern.

Spraying and Sniffing TGLT Systems

Figure 124 From left to right, schematics of spraying and sniffing TGLT systems [9]

To verify existence of a leak and its rate, for industrial and quality control applications, the three used techniques are global measuring, bombing and sniffing with accumulation. Global measuring, as a vacuum technique, involves filling the specimen with a tracer gas, placing it in a chamber connected to an analyzer cell and removing air from it. The detector measures the flow of tracer gas escaping from the specimen through all leaks at the end of the test period. Bombing technique, as another vacuum technique, is used for sealed objects that cannot be directly connected to a detector. The specimen is first placed in a chamber contacting pressurizing tracer gas which penetrates it if there is a leak. Then, the specimen is removed from chamber and placed in a vacuum chamber which is connected to a detector. If there is any leak, the tracer gas escapes from the specimen and it is detected by the detector. In sniffing with accumulation, the specimen is pressurized with the tracer gas and placed under a cover or hood contacting a sniffer probe. The tracer gas from any leak accumulates over time inside the cover and the probe measure its concentration. It is crucial to consider that none of techniques is able to locate the leak but only prove its existence and possibly its rate, plus, in global measuring and sniffing with accumulation the specimen has to be pressurized. The first two techniques are suitable to detect small leaks whereas sniffing with accumulation is useful in detecting large leaks.

Global Measuring, Bombing, and Sniffing with Accumulation TGLT Systems

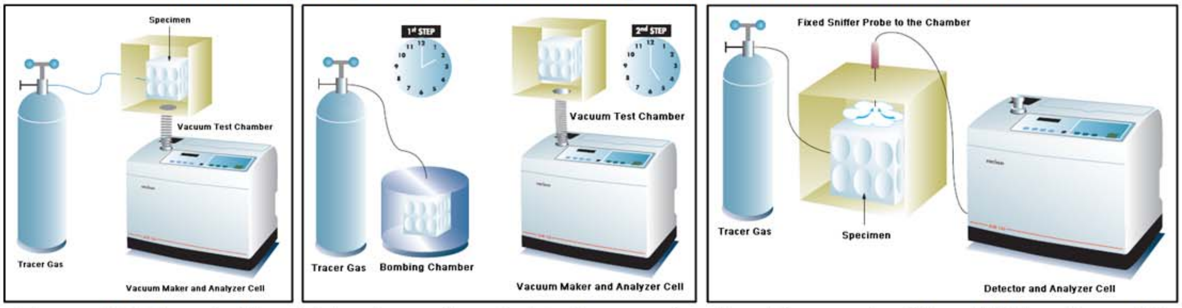


Figure 125 From left to right: schematics of global measuring, bombing, and sniffing TGLT systems [9]

In helium TGLT, a mass spectrometer, a device for sorting charge particles, is used to perform the very sensitive testing. In fact, due to extremely sensitive nature of helium mass spectrometry, care must be taken to differentiate between real leaks that cross any wall or barrier, and permeation of helium through elastomers such as O-rings, gaskets and seals. In general, real leaks appear and decay quickly in a matter of seconds, while permeation takes minutes to take place and remains somewhat constant before slowly dissipating. The maximum sensitivity of a mass spectrometer leak detector (MSLD) is determined by the minimum mass flow of helium tracer gas that generates a measurable signal. This can be limited by the level of ambient helium, electronic noise, and the minimum capabilities of the detector to read current imparted on it by the ion beam. The sensitivity of the detector using a sniffer probe in pressurized volumes is orders of magnitude less than when the leak detector is used to evacuate parts because of helium background entering the sniffer [438]. There are various helium MSLDs available with different configurations; yet, all of them consist of three major components which are spectrometer tube, the vacuum system, and the electronics required for operating the system. A leak detector can serve more than one need in production or maintenance applications providing it has the appropriate features. In spite of the application, there are some basics to be considered before a choice of a proper helium leak detector is made. There are confusing varieties of leak detectors to choose among, and anyone who is unfamiliar with various types will find it complicated to make a definite choice. Some of the factors which have to be taken into account are the method to be used, required sensitivity and response and recovery times of the device [156].

Stationary and Portable Helium Leak Detectors

Figure 126 A stationary and a portable helium leak detector that uses helium mass spectrometers [WS104]

Another tracer gas ideal for spotting leaks of any size is hydrogen. It is actually the lightest element in the universe and hydrogen gas is the lightest of all gases. Consequently, hydrogen is able to evenly flee from the leak not signifying any false location. Hydrogen molecules move with a much higher velocity than any other molecule and therefore escape through leaks quicker than other gases. Hydrogen gas does also dissipate quicker than other gases thereby minimizing the risk for build-up background interference during leak testing. Moreover, it is an environmentally friendly and a renewable natural resource which is quite inexpensive, nontoxic and noncorrosive. When mixed with nitrogen, the solution loses the draw-back feature of the hydrogen, flammability. In fact, hydrogen is only flammable in the concentration range 4%-75% in air or oxygen, and can only detonate in the range 18%-60% in air or oxygen. As said, by using premixed hydrogen-nitrogen one can avoid the flammable concentration range altogether (a suitable concentration to use is the standard 5% hydrogen - 95% nitrogen mixture). Therefore, hydrogen can safely be employed to leak test if it is utilized properly which indeed requires use of an appropriate hydrogen detector.

A Portable Hydrogen Leak Detector

Figure 127 A portable hydrogen leak detector [WS85]

In a VFLT system, a mass spectrometer plugged in a tracer-gas detector, and one or two primary vacuum pumps are used. These pumps can be rotary vane pumps, diaphragm pumps, scroll pumps or any other types of pumps. However, the modern systems employ a turbo pump, a drag pump, or a combination turbo-drag pump as a high vacuum pump. In a single primary pump system, the pump task is to decrease the pressure at the specimen bay or inlet of the leak detector and act as a backing pump for a high vacuum pump. In a dual primary pump system, one pump evacuates the specimen bay and the other is dedicated to backing the high vacuum pump. This configuration permits for longer roughing times without having to switch the pump to a backup mode periodically. The high vacuum pump generates sufficiently low pressure in the spectrometer tube to support proper operation. Additionally, there are accompanying tubes and valves crating a system which let the tracer gas to flow into the spectrometer tube in one or more paths or, in other words, in different arrangements). Leak detector cells have also power supplies that control and regulate the ion source, amplifier, microprocessor, display, and other electronics within. The spectrometer typically has a high vacuum gauge which is operated bay gauge controller. The high vacuum gauge indicates when the source filament needs to be turn off due to excessively high spectrometer pressure. One or more rough vacuum gauges are required as well to monitor manifold pressures and drive valve sequences [438].

There are various versions of wet and dry types VFLT systems. Wet types usually use oil-sealed rotary vane pumps which indeed a proven technology that offers good tracer gas pumping characteristics. On the other hand, there are various choices in the wide range of dry primary pumps which include diaphragm, scroll, multi-stage blower and molecular drag pumps. There are some cases in which the choice of dry primary pump can impact the ultimate sensitivity of the leak detector in a negative way. This may be due to their compression ratios as well as their propensity to let the tracer gas (especially helium) flow backward through them and consequently be appeared as a leak. However, different technologies can be utilized in combination to improve pumping characteristics. It is also important to consider that the cost per unit of pumping speed goes up significantly with the dry pumping technologies [438], [641].

Various Pumps Used in VFLT Systems

Figure 128 Photos of different pumps used in VFLT systems; from left to right: a rotary vane pump, a scroll pump, a turbo-molecular high vacuum pump [WS34]

Ultrasonic leak testing relies on the ability of instrumentation to pick up small acoustic vibrations caused primarily by the turbulent flow of a pressurized gas passing through the leak. Ultrasonic leak testers analyze the turbulent flow of a fluid across a pressure boundary that creates acoustic waves. These waves can be transmitted through the medium of the fluid itself, through the containment structure or through the air surrounding the containment structure. Particular ultrasonic detectors can also be used to hear the noise from a special sound generator as it penetrates the leak in an unpressurized vessel. It is often used as a preliminary gross leak test. Indeed, ultrasonic testing (UT) has become so widely used to test bearings, gearboxes and general mechanical inspection wear trends over time that it is often overlooked in leak detection. In UT leak testing part size is usually not a problem, nor is thermal variation. Arrays of sensors are used to pinpoint a leak. In some instances, pressure change leak testing and mass flow meters have been integrated with ultrasonics to provide increased sensitivity. While this method has not been widely used in manufacturing and processing industry, it has potential for larger parts [586]. Today, there are a variety of ultrasonic instruments available for leak detection in different pressurized systems.

Various Ultrasonic LT Devices

Figure 129 Stationary and handheld ultrasonic devices for leak detection in pressurized systems [WS9], [WS46]

One of the many applications of penetrant testing (PT) is in leak detection by enhancing visual detection of leaks. For leak testing, the liquid penetrant is applied on one side of the enclosing wall or surface of the specimen; after allowing adequate time for the penetrant to seep through leaks, inspections are undertaken on the opposite side of the wall. Such a technique can only be effectively used for leak inspection of empty vessels, tanks, plate-like objects and other liquid containment systems which allow the access to both side of their surface. However, some liquid penetrants can be used to enhance the visibility of leaks in other LT methods such as BELT. For the mentioned objects, the procedure of leak detection via penetrant testing is as follows: First, the operator applies penetrant on the inside wall of the tank or area being inspected. Depending on the thickness of the wall adequate dwell time should be taken (between 10 and 30 minutes up to an hour if the wall thickness is greater than 7 mm). Then, he applies developer on the other side of the wall and looks for possible indications.

Of course, detecting leaking fluid, whether it is water, steam or different types of gases, is of major concern in plants. These leaking fluids can affect safety, operation, maintenance, energy costs, and work performance. Infrared thermography or thermographic inspection enables swift and accurate isolation of leaks particularly in inaccessible or concealed machinery and industrial systems which are normally invisible to the naked eye. Maintenance work can thus be carried cost-effectively and with a minimum of damage to the surrounding area. Each of the techniques, which have been reviewed in this section, has its particular applicability, advantages and disadvantages plus a definite sensitivity range. Depending on the industry, the test object and the accuracy requirement, one may be preferably selected as the ultimate choice among the others.

There are other techniques which have been used in industry for specific applications. For instance, a technique which is particularly used for water leak detection on welds is to use a strip of aluminum foil laid over a wider strip of water soluble paper. The strips are pasted over the welded seams of water-filled specimen. If a leak exists, the water-soluble strip dissolves showing the seep location; plus, the aluminum foil strip will be contact with the specimen which results in a corresponding change in resistance proving the existence of leakage. It has to be noted that such a technique can only be used for electrically conducted material (i.e. metals) and specifically for inspecting the welds.

Table 30 Sensitivity comparison of different leak testing methods and techniques

Method/ Technique	Maximum Sensitivity
Bubble inspection leak testing (immersion)	1x10^{-5} std.cm^3/s
Bubble inspection leak testing (solution/liquid film)	1x10^{-4} std.cm^3/s
Chemical reaction leak testing	1x10^{-8} std.cm^3/s
Gas detection leak testing	1x10^{-4} std.cm^3/s
Halogen diode leak testing	1x10^{-6} std.cm^3/s
Hydrostatic leak testing	1x10^{-4} std.cm^3/s
Pressure change leak testing (pressure rise)	1x10^{-5} std.cm^3/s
Pressure change leak testing (pressure drop)	1x10^{-3} std.cm^3/s
Radioisotope leak testing	1x10^{-13} std.cm^3/s
Tracer gas leak testing (helium spraying)	1x10^{-12} std.cm^3/s
Tracer gas leak testing (helium global measuring)	1x10^{-13} std.cm^3/s
Tracer gas leak testing (helium sniffing)	1x10^{-7} std.cm^3/s
Tracer gas leak testing (multi-gas sniffing)	1x10^{-6} std.cm^3/s
Vacuum flow leak testing (direct flow)	1x10^{-12} std.cm^3/s
Vacuum flow leak testing (reverse flow)	1x10^{-10} std.cm^3/s
Ultrasonic testing for leak detection	1x10^{-3} std.cm^3/s
Penetrant testing for leak detection	1x10^{-4} std.cm^3/s
Thermographic inspection for leak detection	1x10^{-3} std.cm^3/s

Flow measurement, being a process variable in the operation of pipelines, is also employed for leak testing. Several different types of flow meters are used on pipelines including orifice plates, turbine, positive displacement, coriolis mass, and ultrasonic. The flow meters most often installed on pipelines are sharp-edged orifice plates, a differential pressure type of meter. However, their accuracy in pipeline leak detection is doubtful. Although vendors claim orifice plates are accurate to within 0.5% of flow, in practice accuracies better than 3 to 5% cannot be attained (considering fluid composition changes, temperature and pressure variations, conversion and computational errors). Turbine meters have rotors that sense the velocity of flowing liquid in a closed conduit. The flowing liquid forces the rotor to move with a tangential velocity proportional to the volumetric flow rate. Turbine meters are used extensively on pipelines carrying hydrocarbons. Turbine flow meters tend to be more accurate than other types. Their volumetric accuracy depends on the measured dimensions of the pipeline section, the amount of drag in the turbine's rotor, and the degree of system proving [416].

Positive displacement meters measure flow by moving the liquid through a pipe section of known volume. The claimed accuracy of these meters is 0.1 to 0.2% of flow. The accuracy of these meters depends on the accuracy to which the dimensions of the pipe section are known, the extent to which it effectively contains the product, and the temperature and pressure conditions under which the measurements are made. Another flow meter is the coriolis direct mass meter. The accuracy of these instruments is approximately ±0.5% of reading. The ultrasonic transit-time flow meters are installed on the outside of the pipeline. These clamp-on flow meters are reportedly accurate to within 0.03 cm/sec at any flow rate. However, measurement engineers hold the installed accuracy of these meters to be no better than 2% of flow. Nevertheless, ultrasonic meters have the advantages of negligible head-loss and the chance to install additional instrumentation without line shutdown [416].

Various Flow Meters for Leak Detection

Figure 130 From left to right: orifice plate [WS5], turbine [WS90], positive displacement [WS47], coriolis mass [WS13], and ultrasonic flow meters [WS19]

One the crucial topics in leak testing is relating gas flow to liquid leakage which is not a clear-cut task. While it is possible to calculate liquid and gas flow rates through perfectly formed passages, real leaks are far from symmetric. This and the physical differences between the liquid and gas phases essentially prevent exact correlation. Gas is compressible, and its molecules may be bunched closely together or spread out over considerable distance. Liquids, on the other hand, keep nearly the same volume as they flow as their molecules remain the same distance apart. In 1968, Marr proposed that leaks having a gas conductance around 10^{-3} std.cm^3/s have a liquid leakage approximately one-half of that [407]. Gas conductance around 10^{-4} std.cm^3/s seeps liquid approximately one-tenth of this. If the gaseous leakage is in 10^{-5} std.cm^3/s range, its rough liquid leakage is one-twentieth [333].

6.6.3 Use and Applicability

In spite of the significant expansion of gaseous and liquid leak detection in different branches of industry for maintenance purposes and its integration into automatic assembly and test lines for quality control applications, an aura of ambiguity still surrounds the technology. Facts are often slanted by misconceptions, misuses, and wishful thinking, or some combination of thereof. Erroneous information exists, but there is also an apple supply of solid and accurate information. Unluckily, those who need it do not know where to look for it; but if and when they do find it, it usually makes little sense. In the coming paragraphs the author tries to provide brief but extensive information about the use and applicability of leak testing.

Bubble emission leak testing is frequently undertaken in pressurized machinery components and processing tubing or coil systems to identify presence of any costly air, nitrogen and oxygen losses. In pressurized process piping and vessels leak detector solution can detect hazardous (i.e. flammable, explosive or toxic) leaks to the environment. Of course, such pressurized systems must be shut down, depressurized and drained before the leaks can be repaired. After depressurization, leaking valves, flanges, gaskets, or tubing fittings can be replaced [438]. It is important to keep in mind that attempts to tighten a leaking fitting under pressure can lead to blowout in the face of the technician. Immersion BELT can be used on any internally pressurized object (e.g. pressure vessel) that would not be damaged by the test liquid. In fact, this method can be effectively utilized for inspecting the integrity of pressure vessels, valves, piping, circuits, condensers, heat exchangers, pumps and cylinders [501]. Sensitivity of the immersion BELT can be enhanced by reducing the pressure above test liquid, its density and surface tension, and the depth of immersion in the liquid [333].

Chemical reaction leak testing is used to leak test large single and double walled tanks, pressure and vacuum vessels, laminated, lined or double-walled parts, complex piping systems, flexible containers (such as aircraft fuel tanks), glass-to-metal seals in hybrid packages and systems that inherently contain or will contain any potential tracer such as water, ammonia, chlorine or oil [80]. On the other hand, gas detection leak testing can be employed to leak test nearly all types of machinery objects which are containing or using any combustible or toxic gas, in addition to other gases such as oxygen and carbon dioxide. Today, GDLT utilized different stationary probes and handheld equipment with which the operators can easily leak test any industrial object without any risk. The available technologies have almost no limit accessing the location of the test object.

Halogen diode leak testing can be used for inspection of any object which incorporates halogen based fluids such as refrigerants (e.g. refrigerant coils, air conditioning systems). However, using HDLT detectors certain causations are indispensable in the probe explorations. For example, probing too quickly may result in missing small leaks. To avoid such a risk, the speed at which the probe is moved must be in proportion to the minimum leak tolerance. To illustrate, while inspecting a vessel for allowable leaks of the order of 0.001 kg per year, the probe speed must be kept between 2.5 and 5 cm per second; for smaller allowances the probe's speed should be reduced to 1 cm to 1.5 cm per seconds. It has to keep in mind that HDLT detectors should never be employed in explosive atmospheres as its high-voltage circuits and higher heater temperatures may ignite explosive mixtures. Besides, it is crucial to note that although refrigerant gases are considered to be harmless and inert, some like R-12 in the presence of high temperatures can be de-compounded into hydrogen fluorine, chlorine and phosgene which are all toxic are relatively low levels [80], [333].

Coming to the other methods, while hydrostatic leak testing can be used on different piping, tanks, valves and containers with welded or fitted sections, pressure change leak testing is more sensitive for small, contained volumes at test pressure. Meaning that, a small leak in a small, pressurized container will cause a more rapid drop in pressure than the same size leak in a similarly pressurized large container. PCLT is also utilized effectively for small parts on series leak testing in the range of 0.1 to 0.5 std.cm^3/min. It has to be highlighted that in PCLT leaked gas is not captured, measured or analyzed, so the test procedure must compensate for pressure-change effects of ambient, used gas and specimen temperatures as well as its volume [438]. Between the two major PCLT techniques, pressure rise and pressure drop, the latter is more suitable for leak testing large containers such as fuel or fluid tanks. In using the pressure drop technique for large vessels the procedure is as follows: first, the tank is pressurized reaching a safe pressure of about 1.5 bars. Then, an accurate manometer is used to monitor the pressure drop. The leak rate is calculated from the pressure drop in the tank volume during the testing. If a leak larger than the acceptable limit is found, it can be located with BELT or TGLT. In general, sensitivities on the order 10^{-3} and 10^{-4} std.cm^3/s is routine for PCLT, however, better sensitivities of 10^{-5} and 10^{-6} std.cm^3/s have been also reported in industry [333].

Tracer gas leak testing is performed in many industries, including automotive, aerospace, ship technology and petroleum. TGLT is one the most effective leak testing method as with the use of a mass spectrometer it offers one of the highest leak test sensitivities. Leak sensing times can be short, often ranging from 1 to 8 seconds, and test time does not usually increase greatly with the specimen volume. TGLT can be automated and performed at various temperatures. However, while some gases used in this method are inexpensive, the equipment is more expensive than that of other LT methods; furthermore, it will require calibration and usually special cleaning. Besides, while gases such as helium do not pose health risks, some gases are hazardous, and concerns such as toxicity, radioactivity or flammability must be addressed. Spraying TGLT is used for leak testing of vacuum systems (e.g. vacuum chambers and gas panels) and vacuum components such as pumps, valves and gauges. Its quality control feature is performed by manufacturers and maintenance tests are undertaken by the end users. It is important to consider that using this technique the specimen to be tested must be placed under vacuum, thus, the connection between the specimen and the detector must be perfectly tight. Sniffing TGLT is mainly employed to leak test pressurized systems or systems that are usually filled with liquids. Some of it applications are in inspection of refrigeration and air conditioning units, process lines and tubing, and containers and tanks. It is notable that its sensitivity is limited by the tracer gas in background and its response time depends on the length of the sniffer prob.

Global measuring TGLT is usually used to undertake an industrial quality test in a production facility. However, it can be adapted to inspect evaporators, condensers, radiators, compressors and tanks for maintenance purposes. Using this technique, some leaks can be missed if the object to be tested is not pressurized under actual operating conditions. Bombing TGLT is merely used for quality control of small pieces such as sealed semiconductor devices, thermal sensors and so on. Its application for maintenance of small machinery pieces is still under research. It must be kept into account using this technique, it is possible to miss gross leaks, plus, it is usually time consuming particularly in the first step of the testing procedure. Eventually, sniffing with accumulation TGLT is usually utilized to undertake an industrial quality test in a manufacturing facility when a global measuring test cannot be used. It is barely used to test air conditioning systems and aluminum rims in industry. In this technique the volume between the specimen and the test chamber (i.e. the free volume) must be as small as possible for better results.

Vacuum flow leak testing, as an alteration of regular tracer gas leak testing, is employed to test vacuum systems only. In principles and equipment used it is quite similar to some TGLT techniques, however, it is also possible to categorize is a standalone method due to its particular configurations. Indeed, from maintenance perspective many vacuum systems require occasional leak checking. This may be part of a preventative maintenance schedule or in the event of an unexpected failure. Downtime in either case must be minimized running a VFLT. A rugged, dependable, fast starting leak detector is essential to maximize up time of vacuum systems used in production lines. Some vacuum systems which can be tested using VFLT are: vacuum furnaces, vacuum coaters, beam lines and laser process equipment. The use of such a leak test is only limited to some specific facilities and VFLT is not frequently used in manufacturing and processing industry. Nevertheless, some new applications may emerge with upcoming technologies and also imminent requirements in the industry.

Ultrasonic leak detection has been widely used in industry for the systems which cannot be pressurized for the purpose of leak testing in addition to pressure or vacuum systems, seals and gaskets, wind noise, hatch leaks, vacuum bagging, compressed air, compressors, valves, steam traps, heat exchangers, boilers, condensers, building envelope, glove box, and distillation columns. Where ultrasonic leak testing of heat exchangers, boilers and condensers most often involves inspection of three generic areas: tubes, tube sheets and housings. Additionally, pipelines of different materials with various flowing fluids can be effectively tested with UT or AE based leak detection [212], [433], [640].In fact, during a leak, a fluid seeps from a high pressure to a low pressure. As it passes through the leak site, a turbulent flow is generated. This turbulence has strong ultrasound components (i.e. high frequency, short wave signals) which are heard through ultrasound headphones and seen as intensity increments on the equipment's meter. Ultrasonic leak detection is useful for detecting leaks that generates ultrasounds in the frequency range of 30 to 50 kHz, but it is limited to a sensitivity of approximately 10^{-3} std.cm^3/s [333].

For ultrasonic leak testing, the inspection procedure is to scan the general area of a suspected leak and to listen for a hissing or rushing sound (i.e. similar to the sound one hears when filling a tire with air). Then, the operator has to move in the direction of the loudest sound. If it is hard to determine the direction of the noise, it is possible to establish the direction by reducing the sensitivity. In order to confirm the leak site, operator shall move the detector back and forth over the suspected area. The sound level should increase as the detector passes over the leak. In some loud factory environments, frequency tuning may be required as well. Should the unit require off-line inspection, it is possible to use special ultrasonic transmitters with which the unit to be tested is flooded with intense ultrasonic sound waves on the shell side and the other side is scanned for a distinct high pitched warbling sound coming from the leak. While under pressure or vacuum, fittings and casings may also be checked for leakage in a similar manner [438].

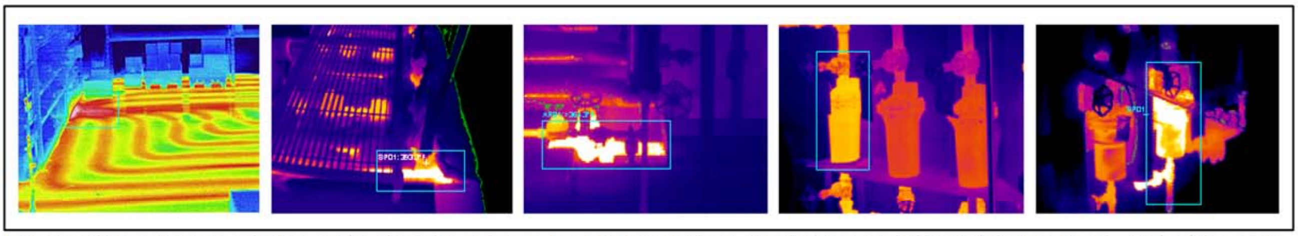
Ultrasonic Leak Testing

Figure 131 Use of a handheld ultrasonic device to detect leaks in piping [WS59]

As explained before, penetrants are also used to detect leaks in empty vessels, tanks, plate-like objects and other liquid containment systems which allow the access to both side of their surface; or, the objects that are small enough to be completely filled with a penetrant. The same basic fundamentals of penetrant testing apply but the penetrant removal step may be overlooked. Usually, the penetrant is applied to one side of the specimen's wall. The developer is applied to the opposite side, which is visually inspected after allowing time for the penetrant to seep through any leak points. This method may be used on thin parts where there is access to both surfaces and the discontinuity is expected to extend through the material. It is essential to consider that as opposed to UT leak detection, such a test using penetrants cannot be effectively used for pressurized systems where the applied stress and associated proof-test factors are significant.

Leak testing using infrared thermography is another method which can be effectively utilized to detect leaking fluids whether it is steam, water or different types of gases and liquids. According to the common industrial practices, thermographic inspection can be used to detect leaks on the following components and systems: valves, pipes, joints, bolts, flanges, welds, steam traps, condensers, pumps, heaters, turbines, tanks, and boiler casings. When combined with ultrasonic leak detection, the effectiveness of these two methods increases noticeably. Confirming a suspected leak detected with one technology by repeating the detection with a separate technology is always a best practice.

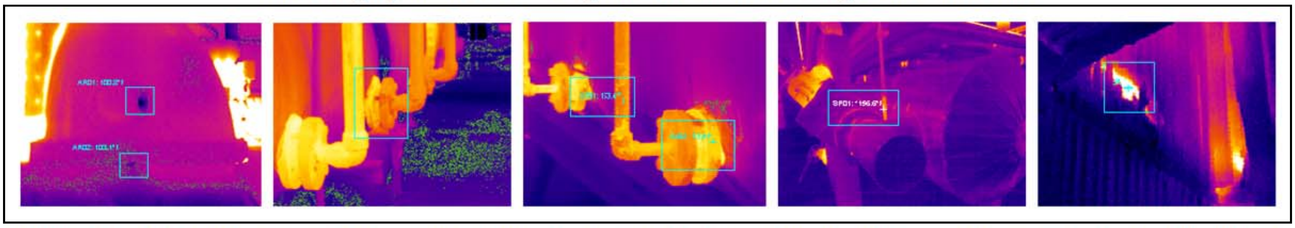
Identifying leaking valves is probably the most effective use of thermographic inspection to diminish fluid or heat losses and operational problems. In fact, temperature is the key to identifying leaking valves where a small temperature rise can indicate a leak through. All valves and lines going to the tanks, pumps, condensers, heat exchangers and boilers can be inspected for leak using this method. However, it is important to make sure that the valve to be tested is totally closed before inspecting. Thermographic inspection can also identify leaking pipes and steam tarps, and their improper operation. Of course, the test operator must know about the trap cycle of operation and with comparison between similar equipment that is operating the same often he can be able to verify existing problems [143]. Indeed, proper reporting of findings by the operators is the key to the successful application of these technologies in upcoming similar cases in a plant.



Thermographic Leak Testing of Pipes, Valves and Steam Traps

Figure 132 Infrared photos of industrial objects leak; from left to right: underground pipeline leak, drain line leak, valve leak, steam trap leak, and steam trap stuck open [143]

A condenser's air in-leakage can be identified with thermography by confirming temperature variations before and after valves, flanges, joints and welds. In this case, detection can be difficult and surface conditions (e.g. paint and rust) always need to be compensated for. Checking a condenser tube sheet for leaks while the unit is on can pinpoint the leaking spots. It is also important to check all bolts, diaphragms and access doors on the condenser and turbine shells. Heaters can also be checked with to identify heat rate loss components. Here, both high pressure and low pressure heaters can be scanned. Moreover, thermographic leak detection is very useful to identify boiler and ductwork casing leaks, which indeed, increase auxiliary power use by increasing load on fans and pulverizers. Eliminating such leaks improves combustion and reduces excess air [143]. In recent years, there have been successful researches on mass quantification of equipment leaks and related technology enhancement using infrared/optical imaging [370], [682].



Thermographic Leak Testing of Condensers, Flanges and Heaters

Figure 133 Infrared photos of industrial objects leak; from left to right: condenser access-cover leak, flange leak (temperature difference between the flange and the connecting line indicates a leak), shell vent vacuum leak, boiler casing leak [143]

Coming to the end of this section, it has to be noted that return on investment is an important factor in selecting the appropriate leak test method and equipment, because if the selected technique and technology deplete budget for any reason, it will soon be demoted to a murky role or discontinued. The requirements and norms to set maximum acceptable leak rate for a given object depend on its task and application. As the cost of leak detection increases with decreasing required leak rate (i.e. higher sensitivity), it follows that leak testing for very tiny leaks will intend unnecessary expenses. On the other hand, the risks associated with a leak are essential as well. To illustrate, for an industrial pump that pumps water the sensitivity requirement and the appropriate LT method is quite different than for the same pump driving toxic, combustible or radioactive liquids, hence, the related leak testing costs. It is beneficial to have an overview of approximate time based equivalent of different gaseous leak rates so that depending on the type and properties of the gas, its leakage risks can be estimated.

Table 31 Approximate time based equivalent of various gaseous leak rates [501]

Leak Rate [std.cm^3/s]	Approximate Time Based Equivalent
10^{-1}	1 cm^3 in 10 seconds
10^{-2}	1 cm^3 in 100 seconds
10^{-3}	3 cm^3 in 1 hour
10^{-4}	1 cm^3 in 3 hour
10^{-5}	1 cm^3 in 24 hour
10^{-6}	1 cm^3 in 2 week
10^{-7}	3 cm^3 in 1 year
10^{-8}	1 cm^3 in 3 years
10^{-9}	1 cm^3 in 30 years
10^{-10}	1 cm^3 in 300 years

Of course, successful implementation of a chosen method requires a practical understanding of all events within the cycle of a complete leakage test in addition to the risks associated with the leak itself. Regardless of sensitivity consideration, the goal of any leak test is to identify and reject any object having total leakage greater than the allowable rate. The allowable rates are set by quality, operation, safety and environmental requirements which vary for every object and its contained fluid. Besides, it has to be underlined that each and every leak detection experience should be recorded communicated through proper reporting in a plant. This is fundamental for developing an effective in-house LT program which can reduce costs (i.e. of material or energy loss) and diminish the all the related risks.

6.6.4 Limitations and Pros

Bubble leak test is the simplest leak testing method and also the most economical one among all. Plus, it requires little operator skill for low-sensitivity testing and enables the operator to locate the leak accurately, in addition to be very inexpensive, fast, safe, sensitive and reliable. It can also be used even when there is no access to the opposite side of the object (i.e. required by some other testing methods). Nevertheless, the test object must remain unaffected by the immersion fluid. The immersion BELT can only be used for small objects being pressurized for the test and leak size is difficult to be estimated.

However, if the object is sealed at atmospheric pressure, a pressure differential can be obtained by pumping a partial vacuum over the liquid or by heating the liquid. In case of using bubble forming solutions, the merit is that test can be applied for the objects which are too large or unmanageable to be immersed but again the demerit is that the test does not generally allow the operator to verify the size of a leak accurately. In general, using foams or liquid films, the inspected object requires cleaning after the test. It is also crucial to keep in mind that some leaks have been known to pass gas in one direction only, and if this is inward, the BELT method is not able to locate such leaks [501].

Coming to the chemical reaction leak testing, indicator tapes are still widely used as: remote control of the tapes is possible that ensures safety for the operators; it has relatively high sensitivity; the color of tapes is not affected by hand contacts, high humidity or the passage of time; plus the tapes can be used more than once if the reaction spots are removed by blowing the tape with dry compressed air. The technique of ammonia and hydrochloric acid or sulfur dioxide reaction is operator independent, inexpensive, very sensitive and rapid. However, such techniques require very good ventilation due to noxious characteristics of ammonia gas, hydrogen chloride and sulfur dioxide. Besides, ammonia as a tracer can corrode brass or copper, deteriorate woods, and in large quantities be toxic. Therefore, the potential downsides of running such chemical reactions to the operator’s health and also environment have to be always kept in mind, and the test object has to be entirely cleaned after the test.

Gas detection and halogen diode leak testing, by means of handheld devices or fixed instruments, are quite operator independent and cheap. Indeed, it is usually difficult to exactly locate the leak(s) using such instruments; nevertheless, they are highly capable of alarming the existence and severity of a wide range of gases from oxygen to very toxic or even combustible ones. Although, these tests are not belonged to very sensitive category of leak testing methods but they are among the most frequently used in manufacturing and processing industries. The low prices of required instruments, extreme ease of use, and their accident-preventive contributions make them one of the fix choices of every leak testing program in industry.

Hydrostatic leak testing, when conducted properly, can attain the same sensitivity as leak test undertaken using liquid penetrants on bulky objects. It is relatively operator independent, quite inexpensive; and, it pinpoints available leaks. This test using dye penetrants is approximately twice more sensitive on objects with smaller volumes. However, using water alone as the test fluid does not result in a very sensitive test. The disadvantages involve high pressure used, the amount of time consumed, and the significant cleaning required after the test (i.e. using other liquids rather than water or employing penetrants for better results). It is also important to note that this test may obscure leaks if a more sensitive leak test is to be used afterwards.

Pressure change leak testing, as one the commonly used test in industry, has the advantage that total leakage rate can be measured on both evacuated and pressurized systems and on any size system. Besides, it is safe and operator independent; and, no special tracer gas is required to run the test. However, it is not easy to attain very accurate result on large vessel-like objects. The test is very time consuming and requires trained personnel and advance devices. And nevertheless, it does not provide the leak location but only the leak rate [438]. The merit of radioisotope leak testing is that even nano leaks can be easily identified; however, for such an advantage the price is higher prices and the associated safety issues. Therefore, except for very special applications in limited number of industries, such a test is not widely used.

From an industrial perspective, the advantages of tracer gas leak testing, particularly when helium is used as the tracer gas, are many. In general, leak rates can be identified and measured for all practical requirements; it is possible to automate the testing and procedure; helium is a nontoxic, cheap and safe tracer gas; plus, leak rates for every specimen can be quantitatively recorded [202]. To be more precise and provide a comparison, spraying technique has the advantage of high sensitivity and ease of perform in addition to be both local and global test (i.e. locating leaks and measuring leak rates). Sniffing tracer gas leak testing has the ability to accurately locate any leak. Besides, the specimen does not need to be placed under vacuum for the test. It is very easy to perform and also relatively cheaper than other TGLT techniques. Global measuring has also high sensitivity plus incorporating high throughput and easy integration in series inspection or production lines. The advantages of bombing technique are that it is the only solution to leak test sealed components with high sensitivity plus it enables high throughput. Eventually, sniffing with accumulation as a global test can be easily integrated in series inspection or production lines.

In recent years, hydrogen has been also employed as tracer gas in TGLT. Hydrogen is normally used in a safe mixture of 5% hydrogen in nitrogen. Hydrogen is the cheapest tracer gas available, and is also the lightest and least viscous of all gases, spreading rapidly throughout the test object and seeping quickly through the smallest leaks. A further benefit claimed for hydrogen is that the molecules do not stick to surfaces as easily as helium, giving fewer problems with background interference and residual gas in tested components. Using hydrogen as tracer gas is particularly beneficial to test objects of complex shapes for which the leaks need to be located as quickly and accurately as possible to enable repairs. Besides, it is usually employed to rapidly locate leaks in vacuum systems where due to gross leaks or considerable moisture, leak locating can be extremely time consuming or impractical. For systems that run-on or contain hydrogen such as electrolyzers, reformers or even fuel cells, hydrogen tracer gas leak testing is the most appropriate method to be used. Hydrogen TGLT is particularly attractive for regular testing during ongoing operations, where there is a need to avoid system operation stoppages and downtime [85].

Utilizing ultrasonics for leak testing is practical in detection of both vacuum and pressure leaks. Leaks can be detected up to 15 meters away from source depending on sensitivity of the UT device employed. Plus, it is easy to be used and one of the inexpensive LT techniques among the ones with electronic devices. It can be generally noted that the larger the leak, the greater the ultrasound level. Moreover, the intensity of the ultrasound produced by a leak drops off rapidly as the sound moves away from its source. For this reason, the leak sound will be loudest at the leak site. Ultrasound is considered fairly directional and therefore, locating the source (i.e. the location) of the leak is quite simple [333]. On the other hand, the ambient noise may interfere if it is in the frequency range of the device, and it is somewhat operator dependent.

Employing penetrants for leak testing is also useful as it produces an easily seen leak indication especially when florescent penetrants and black light are employed. Moreover, it does not require pressurizing the system as medium pressure is sufficient to run the test. However, the test procedure is messy and requires significant cleanup afterwards. It can be relatively expensive for very large objects. And, the test using florescent penetrant necessitates a dark testing area [438]. Thermography can be also employed for various leak detection applications. Such a method is quite effective for identification of gross leaks particularly in inaccessible areas. Leak testing using thermographic cameras are also quite cost effective as the equipment are used not only for the purpose of leak testing but also for a wide range of nondestructive and condition monitoring applications in a plant. Nevertheless, the test is only able to locate leaks but it is almost incapable of quantifying the leak rate overlooking the very recent and quite complex and expensive technologies. In practice, however, it is one of the most widely used methods in all branches of industry.

Eventually, it has to be underlined that similar to other forms of nondestructive tests and condition monitoring techniques, leak testing has a great impact on the safety or performance of a mechanical system. From maintenance perspective, reliable leak testing saves costs by reducing the number of potential failures and hence rising the availably of systems. The time and money invested in leak testing often generate immediate profit. The three most common reasons for performing a leak test are as followings: (1) Material loss - with the high cost of material and energy (i.e. from lubricating oil and fuels to expensive chemicals and even compressed air), its loss is increasingly important from an economic outlook. (2) Pollution - with increasing quality and environmental regulations, this reason for testing is growing rapidly. (3) Reliability - with current component reliability and safety requirements, this has long been a major reason for leak testing. Indeed, leak tests operate directly to assure serviceability of critical and to prevent leakage of dangerous gases or liquids which pollute the environment and create serious personnel hazards.

Table 32 Synopsis of leak testing

Pros	▪ Relatively inexpensive ▪ Minimum skill required ▪ No serious safety hazard ▪ Relatively easy to perform ▪ Minimum part preparation ▪ Sensitive to very small leaks ▪ Inspection of inaccessible areas ▪ Applicable to almost all materials ▪ Some portable equipment are available ▪ Effective for series or production inspection ▪ Accurate and permanent test record obtained ▪ Required level of skills and training is not very high for most of methods ▪ As a versatile test, can be used for inspection of complex geometries and various sizes
Limitations	▪ Relatively slow rate of inspection ▪ Results are not fully instantaneous ▪ Mobility (depending on the method used) ▪ The process is sometimes messy (depending on the method used) ▪ Sometimes object preparation required (depending on the method used) ▪ Sometimes significant cleaning of the specimen is required after the test ▪ Sometimes sensitive to background condition (depending on the method used) ▪ Sometimes high level of object cleanliness required (depending on the method used)
Equipment	▪ Handheld, portable or fixed (small to large size) units depending on testing method, associated requirements, object to be tested and sought level of sensitivity
Detectable Failure	▪ Potential failures of machinery or equipment components due to the leakage of contained liquid or gas
Discontinuity types	▪ Weld defect ▪ Surface-breaking crack through the object's wall
Discontinuities size	▪ Many recent LT technologies can identify leakages at scale of microns or even less ▪ The best reported test sensitivity in practice is $1x10^{-13}$ std.cm^3/s for RILT and helium global measuring TGLT methods
Relative inspection cost	▪ Relatively inexpensive in terms of both man power and required equipment; nevertheless, the costs are dependent on the method used (e.g. some handheld and portable equipment for GDLT or HDLT are below 200 €, but the equipment required to run a TGLT or VFLT may vary up to 10,000 €). ▪ Relative minimal expense combined with large savings opportunities will most result in a very short equipment payback period.

6.7 Magnetic Particle Testing

Magnetic particle testing (MT) methods, also known as magnetic particle inspection, are based on the collection of loose magnetic particles at locations of magnetic flux leakage on an object. This phenomenon is familiar to almost everyone from childhood experiments with magnets and iron filings. Magnetic particle methods are based on surface or near surface discontinuities that influence the electromagnetic properties of the object under test. For these methods to be employed, the object under test must be electrically conductive and ferromagnetic. Magnetic particle techniques thus allow the detection of surface-breaking cracks in steel objects of complex geometry, which typically is a challenge for other nondestructive tests.

6.7.1 Conception

Magnetic particle testing or inspection uses the tendency of magnetic lines of force or flux of an applied field to pass through the metal rather than through the air. A defect at or near the metal's surface distorts the distribution of the magnetic flux and some of the flux is forced to pass out through the surface. The field strength is increased in the area of the defect and opposite magnetic poles form on either side of the defect. Fine magnetic particles applied to the part are attracted to these regions and form a pattern around the defect. The pattern of particles provides a visual indication of a defect. The materials commonly used for this purpose are black iron particles and red or yellow iron oxides. In some cases, the iron particles are coated with a fluorescent material enabling them to be viewed under a UV lamp or black light in darkened conditions.

Crack Detection by Magnetic Particle Testing

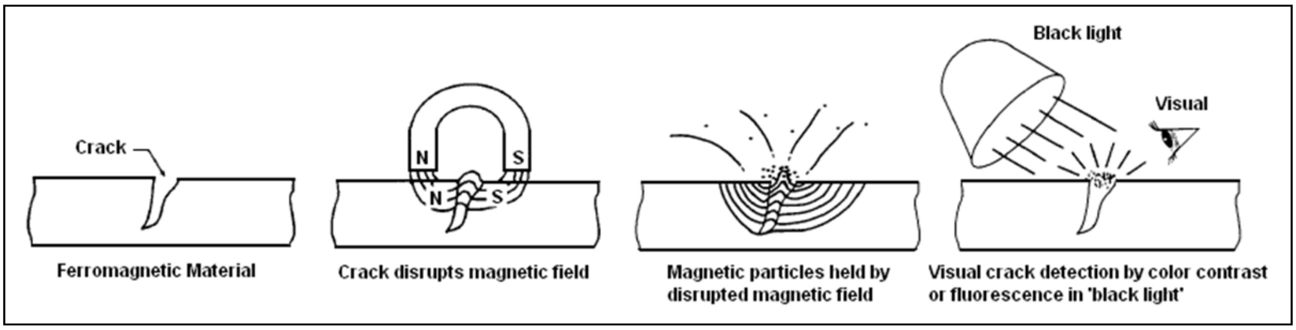


Figure 134 An abstract drawing of crack detection process by magnetic particle testing [190]

1. *Dry Particle Inspection:* In this magnetic particle testing technique, dry particles are dusted onto the surface of the test object as it is magnetized. Dry particle inspection is well suited for the inspections conducted on rough surfaces. When an electromagnetic yoke is used, the AC or half wave DC current creates a pulsating magnetic field that provides mobility to the powder.

   In dry particle inspection, the surface should be relatively clean but this is not as critical as in other nondestructive testing methods such as liquid penetrant inspection. The surface must be free of grease, oil or other moisture that could keep particles from moving freely. A thin layer of paint, rust or scale will reduce test sensitivity but can sometimes be left in place with adequate results. Specifications often allow up to 0.075 mm of a nonconductive coating (e.g. paint) and maximum thickness of 0.025 mm of a ferromagnetic coating (e.g. nickel) to be left on the surface. Any loose dirt, paint, rust or scale must be removed. After dusting on a light layer of magnetic particles one can gently blows off the excess powder with magnetizing force still being applied. Following this, with terminating the magnetizing force (permanent magnets can be left in place) technician looks for areas where the magnetic particles are clustered [385].

2. *Wet Suspension Inspection:* Wet suspension (magnetic particle) inspection, more commonly known as wet magnetic particle inspection, involves applying the particles while they are suspended in a liquid carrier. Wet magnetic particle inspection is most commonly performed using a stationary, wet, horizontal inspection unit but suspensions are also available in spray cans for use with an electromagnetic yoke. Just as is required with dry particle inspections, the surface should be relatively clean.

Test conditions and specifications are also taken into account as the same of dry particle inspection. The suspension has to be gently sprayed or flowed over the surface of the part. Usually, the stream of suspension is diverted from the part just before the magnetizing field is applied. The magnetizing force should be applied immediately after applying the suspension of magnetic particles. When using a wet horizontal inspection unit, the current is applied in two or three short busts (e.g. 0.5 second) which helps to improve particle mobility. Surface discontinuities will produce a sharp indication via clustered particles. The indications from subsurface flaws will be less defined and lose definition as depth increases [385].

3. *Magnetic Rubber Inspection:* This technique uses a liquid (uncured) rubber containing suspended magnetic particles. The rubber compound is applied to the area to be inspected on a magnetized component. Inspections can be performed using either an applied magnetic field, which is maintained while the rubber sets (active field), or the residual field from magnetization of the component prior to pouring the compound. A dam of modeling clay is often used to contain the compound in the region of interest. The magnetic particles migrate to the leakage field caused by a discontinuity. As the rubber cures, discontinuity indications remain in place on the rubber.

   Regarding the procedure, the rubber has to be let to completely set, which takes from 10 to 30 minutes. Then after, the rubber cast is removed from the part. The rubber conforms to the surface contours and provides a reverse replica of the surface and the rubber cast is examined for evidence of discontinuities, which appear as dark lines on the surface of the molding. Moreover, the molding can be retained as a permanent record of the inspection. Considering the magnetization method, this technique requires similar ones as for dry particle inspection. The magnetizing system may include yokes, prods, clamps, coils or central conductors. Alternating, direct current, or permanent magnets may be used to draw the particles to the leakage fields. Nevertheless, the direct current yoke is the most common magnetization source for magnetic rubber inspection [385].

6.7.2 Tools and Techniques

In locating a defect it is essential to control the direction of magnetization and flux lines, which must be perpendicular to the longitudinal axes of expected defects. Examination of critical areas for defects may require complete disassembly. Two methods of magnetization, circular and longitudinal, are used to magnetize the part and induce perpendicular flux paths. Parts of complex configuration may require local magnetization to ensure proper magnetic field direction and adequate removal of surface coatings, sealants, and other similar compounds. Possible adverse influence of the applied or residual magnetic fields on delicate parts such as instruments, bearings, and mechanisms may require removal of these parts before performing the inspection. The particles used in magnetic particle inspection are finely divided ferromagnetic materials that have been treated with color or fluorescent dyes to improve visibility against the various surface backgrounds of the parts under inspection. Magnetic particles, particle-suspension vehicles, and cleaners are required for conducting magnetic particle inspection. Moreover, magnetization is of great importance in MT and can be done in either circular or longitudinal (with or without use of permanent magnets and electromagnetic yoke) ways.

The method of magnetization depends on the geometry of the component and whether or not all or only part of the specimen is to be magnetized. Permanent magnets are attractive for on-site inspection, as they do not need a power supply. However, they tend only to be used to examine relatively small areas and have to be pulled from the test surface. Despite the need for their own power supply, electromagnets (yokes) find widespread application. Their main attraction is that they are easy to remove (once the current has been switched off) and that the strength of the magnetic field can be varied. For example, an AC electromagnet can be used to concentrate the field at the surface where it is needed. Hand-held electrical prods are useful in confined spaces. However, they suffer two major disadvantages that can rule out their use altogether. Firstly, arc strikes can occur at the prod contact points and these can damage the specimen surface. Secondly, because the particles must be applied when the current is on, the inspection becomes a two-man operation. Bench units are fixed installations used to test large numbers of manufactured specimens of various sizes. The electrical components of a mobile unit (as described above) are incorporated in the bench unit making testing more rapid, convenient and efficient.

For such a purpose, stationary equipment in the range of 100 to 6000 amperes is usually used within different manufacturing industries for maintenance and overhaul operations. Mobile equipment with similar amperage outputs is also available for field examination of heavy structures that are hardly movable. Small parts and local areas of large components can be adequately checked with the use of small, inexpensive permanent magnets or electromagnetic yokes. Importantly, the maximum rated output should be greater than the required examination amperage. Actual current flow through a complex part may be reduced as much as 20 percent by the resistance load of the rated output.

Circular Magnetization

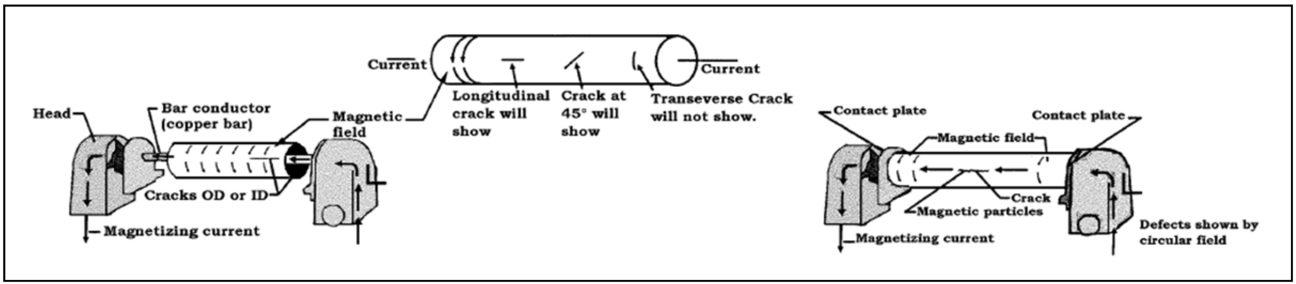


Figure 135 A schematic showing circular magnetization of an item, denoting that transverse cracks cannot be identified in this method [190]

Longitudinal Magnetization

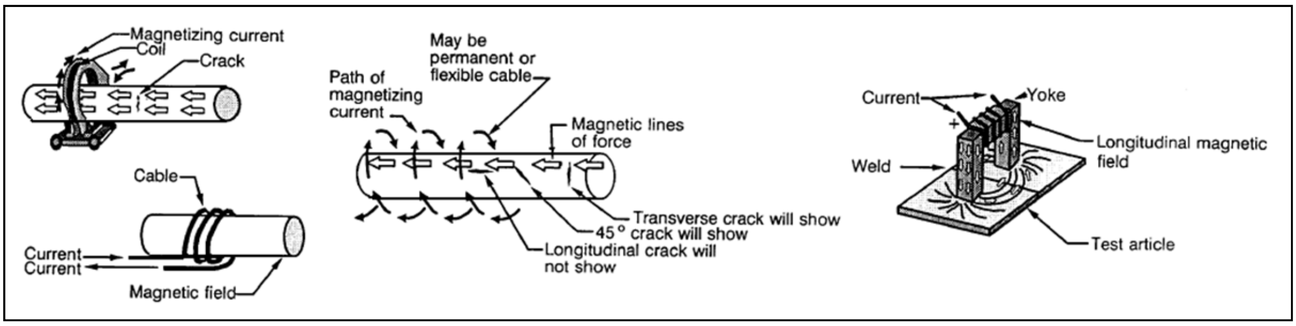


Figure 136 A schematic showing different ways of longitudinal magnetization of an item: coil shot, cable wrap and yoke, denoting that longitudinal cracks cannot be identified in this method [190]

6.7.3 Use and Applicability

MT is useful for detecting cracks, laps, seams, voids, pits, subsurface holes, and other surface or slightly subsurface discontinuities in ferromagnetic materials. MT methods can be used only on ferromagnetic materials (i.e. iron and steel). The test can be performed on raw material, billets, semi-finished and finished materials, welds, and in-service assembled or disassembled parts. Nevertheless, this test should not be performed with coatings in place that could prevent the detection of surface defects in the ferromagnetic substrate. Such coatings include paint or chrome plate thicker than 0.07 mm, or ferromagnetic coatings such as electroplated nickel thicker than 0.03 mm. Moreover, parts should be free of grease, oil, rust, scale, or other substances which will interfere with the examination process. If required, test objects have to be cleaned by vapor degrease, solvent, or abrasive means per the manufacturer's instructions. Abrasive cleaning has to be used only when necessary to completely remove scale or rust. Excessive blasting of parts can affect examination results.

As mentioned in previous sections, magnetic particles are usually applied over a surface either dry (e.g. as a powder), or wet (e.g. as particles in a liquid carrier such as oil or water). Common use for magnetic particle inspection is in receiving, in-process and final inspection of equipment and products regarding quality control, maintenance and overhaul. It is vital to use magnetic particle inspection on well-cleaned surfaces that are accessible for close visual examination. Typical parts deserving magnetic particle examination are: steel fasteners and pins, critical structural elements, linkages, splice and attach fittings and actuating mechanisms. It is important to note that MT examination of assembled bearings is not usually recommended because the bearings are difficult to demagnetize. If a bearing cannot be removed, it should be protected from the magnetic particle examination materials and locally magnetized with a magnetic yoke to limit the magnetic field across the bearing.

The main applications for dry powders are ungrounded welds and rough as-cast surfaces. Dry particle inspection is also used to detect shallow subsurface cracks. Dry particles with half wave DC is the best approach when inspecting for lack of root penetration in welds of thin materials. Half wave DC with prods and dry particles is used when inspecting large castings for hot tears and cracks. Though, wet suspension inspection has several advantages over a dry inspection. First, all of the surfaces of the component can be quickly and easily covered with a relatively uniform layer of particles. Second, the liquid carrier provides mobility to the particles for an extended period of time, which allows enough particles to float to small leakage fields to form a visible indication. Wet inspection is suitable for detecting very small discontinuities on smooth surfaces. On rough surfaces, the particles can settle in the surface valleys and loose mobility, rendering them less effective than dry powders under these conditions. This method is also employed for environmental damage on the inside of vessels.

The magnetic rubber technique was developed for detecting very fine cracks and is capable of revealing finer cracks than other magnetic techniques. The technique can be used to examine difficult to reach areas, such as the threads on the inside diameter of holes. The tradeoff, of course, is that inspection times are much longer. All in all, magnetic particle testing is usually used to detect surface-breaking and near-surface flaws in ferromagnetic materials. It cannot, however, be used to detect deeply embedded flaws, nor can it be used on non-ferromagnetic materials, such as aluminum, copper or austenitic stainless steel. It is also often used to look for cracking at welded joints and in areas identified as being susceptible to environmental cracking (e.g. stress corrosion cracking or hydrogen induced cracking), fatigue cracking or creep cracking. This technique as well as eddy current and ultrasonics are frequently employed to check and examine fasteners, bolts, nuts and rivets [55].

6.7.4 Limitations and Pros

MT is particularly sensitive to surface-breaking or near-surface cracks, even if the crack opening is very narrow. However, if the crack runs parallel to the magnetic field, there is little disturbance to the magnetic field and it is unlikely that the crack will be detected. For this reason it is recommended that the inspection surface is magnetized in two directions at 90° to each other. Alternatively, techniques using swinging or rotating magnetic fields can be used to ensure detectability of all crack orientations. Certain characteristics inherent in the magnetic particle method may introduce errors in examination results. Irrelevant errors are caused by magnetic field distortions due to intentional design features, such as: Sharp radii, less than 2.5 mm radius in fillets; thread roots, keyways, and drilled holes; and abrupt changes in geometry or in magnetic properties within the part. Thus, operators must understand irrelevant error indications and recognize them during examination. Proper analysis of indications in these regions will require considerable skill and experience, and supplemental methods may be required before a final evaluation can be made. MT can leave residual fields which subsequently interfere with welding repairs. These can be removed by wiping the surface with an energized AC yoke.

Table 33 Synopsis of magnetic particle testing

<table>
<tr><td>Pros</td><td colspan="3">▪ Portable
▪ Relatively fast
▪ Immediate results
▪ Moderate skill required
▪ Relatively easy to operate
▪ Sensitive to small discontinuities
▪ Detects both surface and subsurface discontinuities</td></tr>
<tr><td>Limitations</td><td colspan="3">▪ Surface must be accessible
▪ Insensitive to internal defects
▪ Rough surfaces interfere with test
▪ Coating may mask defect indication
▪ Applicable only to ferromagnetic materials
▪ Test object must be demagnetized afterwards
▪ Part preparation such as removal of finishes and sealant required
▪ Efficiency is dependent correct use of flux and current level for item under inspection</td></tr>
<tr><td>Equipment</td><td colspan="3">▪ Magnetic particle or liquid rubber, magnetization means and black light</td></tr>
<tr><td>Discontinuity types</td><td>▪ Void
▪ Hole
▪ Burst
▪ Seam
▪ Crack</td><td>▪ Creep
▪ Pitting
▪ Hot tear
▪ Inclusion
▪ Cold shut</td><td>▪ Corrosion
▪ Lamination
▪ Stress crack
▪ Surface-breaking
▪ Near-surface crack</td></tr>
<tr><td>Discontinuities size</td><td colspan="3">▪ Large to very fine cracks are detectable</td></tr>
<tr><td>Relative inspection cost</td><td colspan="3">▪ It is relatively inexpensive and equipment costs are modest</td></tr>
</table>

6.8 Penetrant Testing

Methods of penetrant testing (PT), also known as liquid penetrant or dye penetrant testing, are simple, and are commonly used for the detection of surface breaking discontinuities, especially cracks. These methods involve the application of a penetrant liquid to the test object, subsequent removal of excess penetrant, and application of a developer to enhance the visibility of remaining penetrant. Surface breaking cracks may trap penetrant, and thus provide a visual indication of the crack. Liquid penetrant methods are popular due to their simplicity and visual nature of the results. The process parameters of penetrant and developer dwell time and cleaning are extremely important, and significant efforts continue to be expended to understand and optimize these parameters. Liquid penetrant methods can be applied to virtually any material, but residual stress fields may close cracks and reduce the effectiveness of these methods [204].

6.8.1 Conception

Penetrant testing is an NDT method that utilizes the principle of capillary action in which liquid of suitable physical properties can penetrate deep into extremely fine cracks or pitting that are opened to the surface without being affected by the gravitational force. PT consists in depositing on the specimen surface of a special liquid, which will be drawn into any surface defect by capillary action. A liquid with high surface wetting characteristics is applied to the surface of the part and allowed time to seep into surface breaking defects. Removal of excess penetrant with application of a developer, which is usually a dry powder carried in a non-aqueous solvent, reverses the capillary action and reveals the presence of the flaw so that it can be visually inspected and evaluated [296].

Penetrant testing is used on nonporous metal and nonmetal components to find material discontinuities that are open to the surface and may not be evident to normal visual inspection. The specimen must be clean before performing a penetrant inspection. The basic purpose of such a test is to enhance the visible contrast between a discontinuity and its background. This is accomplished by applying a liquid of high penetrating power that enters the surface opening of a discontinuity. Excess penetrant is removed and a developer material is then applied that draws the liquid from the suspected defect to reveal the discontinuity [190]. The visual evidence of the suspected discontinuity can then be seen either by fluorescence under black ultraviolet light or by a color contrast in normal visible white light or. Fluorescent penetrants (regularly known as Type I dyes) are more sensitive than visible penetrants because the eye is drawn to the glow of the fluorescing indication. However, visible penetrants (regularly known as Type II dyes) do not require a darkened area and an ultraviolet light in order to make an inspection. Visible penetrants are also less vulnerable to contamination from things such as cleaning fluid that can significantly reduce the strength of a fluorescent indication [622].

Penetrants are also categorized based on the strength or detectability of the indication that is produced for a number of very small and tight cracks. The common-standard five sensitivity levels are: Level ½ - ultra-low, level 1 - low, level 2 - medium, level 3 - high and level 4 - ultra-high. Formerly, there were only four planned levels. However, when some penetrants were judged to have sensitivities significantly less than most others in the level 1 category, the ½ level was created [199]. Despite, penetrant testing is usually classified by the method used for excess dye removal. In practice, there are three main methods which are also called as processes: water washable, solvent removal and post emulsified. These are briefly explained in the followings [622]:

1. ***Water Washable:*** Water washable penetrants (WWP) in this method, which is also commonly called as method A, can be simply removed from the specimen by rinsing with water. These penetrants contain an emulsifying agent (i.e. detergent) that makes it possible to wash the penetrant from the part surface with water alone. Indeed, the detergent acts as an additive which emulsifies the oil in the dye making it soluble in water.

2. ***Solvent Removable:*** Solvent removable penetrants (SRP) in this method, which is also commonly called as method C, require the use of a solvent to remove the penetrant from the specimen. SRPs are usually supplied in aerosol cans and applied to the specimen's surface; excess dye is then wiped away with a lint free cloth.

3. *Post Emulsifiable:* Post emulsifiable penetrants (PEP) are employed in two different methods: lipophilic and hydrophilic, which are also commonly called as method B and method D accordingly. In case of a lipophilic PEP, the penetrant is oil soluble and interacts with the oil-based emulsifier to make removal possible. On the other hand, hydrophilic PEP uses an emulsifier that is a water soluble detergent which lifts the excess penetrant from the surface of the part with a water wash. In post emulsifiable method, the emulsifier is applied just prior to the wash. The emulsification stage is critical since too short a time means that all excess dye will not be removed causing contrast reduction, too long a time and the dye will be removed from the discontinuities making detection more difficult [88], [552].

Table 34 Rough comparison of different PT Methods [WS15]

PT Method	Specimen Size	Specimen Type	Specimen Shape	Batch Size	Sensitivity	Cost
Water Washable	Small - Medium	Good on rough surfaces e.g. castings and forgings	Any, provided that it is easy to be washed	Any (ideal for automation)	Poor	Cheapest
Solvent Removable	Small - Large	Any, with reasonable surface finish e.g. welds	Any, particularly useful for external inspection	Small (it is time consuming)	Good	Fairly expensive
Post Emulsifiable	Small	Precision machined or good finished	Can be complex, useful for internal inspection	Small	Excellent	Most expensive

Regardless of the PT method used, there are five common major steps to perform penetrant testing. These can be named and explained as:

- *Pre-cleaning* - at this stage, surface of the inspected item is cleaned to avoid the presence of any dirt that may close the opening of discontinuity. Cleaning is accomplished by various methods such as vapor cleaning, degreasing, ultrasonic cleaning etc.
- *Penetrant appliance* - once the surface is cleaned, penetrant either in the form of dye penetrant or fluorescence penetrant is then applied. The application of penetrant can be achieved either by dipping, spraying or brushing depending on the nature or item to be inspected. This penetrant is then allowed to remain on the surface for some duration. Such duration is termed as a dwell time. During this period, if there is any discontinuity, penetrant will penetrate deep into it.
- *Excess penetrant removal* - excessive penetrant need to be removed from the surface to allow inspection to be made. Such removal can be achieved by applying water, proper solvent or emulsifier followed by water (depending on the type of penetrant used) on the surface. At this stage, all unwanted penetrant will be removed from the surface, leaving only those trapped inside the discontinuity.
- *Developer appliance* - developer is then applied to the surface of the inspected item. This developer either in the form of dry powder or wet developer acts as a blotting paper which draws penetrant out of the discontinuity. In doing so, penetrant will bleed to form an indication whose shape depends upon the type of the discontinuity presence in the material. Such an indication is recorded either by the application of a special tape or by taking its photograph for interpretation.
- *Post-cleaning* - application of penetrant and developer causes the surface to be contaminated. Thus, upon completion of the inspection, it is important for the item to be cleaned so that no corrosive material remains on its surface that may affect its serviceability.

One of the most important steps in undertaking PT is pre-cleaning or pre-wash. This is due to the fact that improper cleaning methods can cause severe damage or degradation of the object being cleaned. Thus, personnel must and apply cleaning process in accordance with manufacturer's recommendations. In pre-cleaning, contaminants have to be removed from specimens prior to the application of penetrant materials. This is done via use of cleaners. The following cleaners are commonly used during the PT process [222], [329], [552][459], [520], [531], [601]:

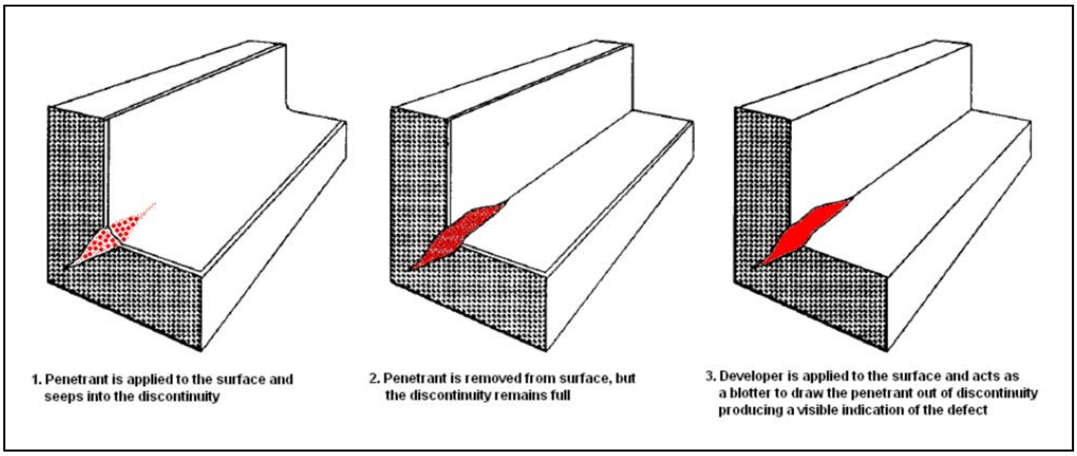
- *Acids* - Solutions of acids or their salts are used to remove rust, scale, corrosion products, and dry shop contamination. The type of acid used and its concentration depends on the specimen's material and contaminants to be removed.
- *Alkalis* - Alkaline cleaners are water solutions of chemicals that remove contaminants by chemical action or displacement rather than dissolving the contaminant.

- *Detergents* - Detergent cleaners are water-based chemicals called surfactants, which surround and attach themselves to particles of contaminants allowing them to be washed away.
- *Etching chemicals* - Etching chemicals contain a mixture of acids or alkalis plus inhibitors. They are used to remove a thin layer of surface material, usually caused by a mechanical process, which may seal or reduce the opening of any discontinuities. The type of etching solution used depends on the part material and condition.
- *Paint removers* - The general types of removers used for conventional paint coatings are solvent, bond release, and disintegrating.
- *Salt baths* - Molten salt baths are used in removing heavy, tightly-held scale and oxide from low alloy steels, nickel, and cobalt-base alloys, and some types of stainless steel. They should not be used on aluminum, magnesium, or titanium alloys.
- *Solvents* - Solvents dissolve contaminants such as oils, greases, waxes, sealants, paints, and general organic matter so they can easily be wiped away or absorbed on a cloth. They are also used to remove Method C penetrant material prior to developer application.

Coming to the application of penetrant, the most important trait that affects the ability of a penetrant to penetrate a surface opening is that of wetability. Wetability is a trait of a liquid and its response to a surface. If a drop of water is placed on a very smooth, flat surface, a droplet with a very pronounced contour will result. Thus, although water is a liquid and is wet, its wetability is not good enough to make it an effective penetrant. In the case of a liquid penetrant, its wetting characteristics should be so great that it will essentially lie almost flat on a smooth surface. Two other important characteristics of the penetrant are the dye concentrations and the viscosity. Dye concentration has a direct effect on the seeability of sensitivity of the penetrant material. Higher dye concentration makes the penetrant more visible to the human eye. Viscosity is defined as the state or quality of being viscous. The viscosity value will affect the actual dwell time, or the amount of time that is required for the liquid to effectively penetrate into an existing surface opening.

Emulsifiers and removers are used in PT to break down and remove excess surface penetrant material. For the emulsifiers to be effective they should possess certain features including that the reaction of the emulsifier with any entrapped penetrant in a discontinuity should be minimal to assure maximum sensitivity. The emulsifier must also be compatible with the penetrant. Plus, it must readily mix with and emulsify the excess surface penetrant. And, the emulsifier mixed with the penetrant must be readily removable from the surface easily (e.g. with a water spray). Solvent removers should also readily mix with the penetrant residue and be capable of removing the final remnants from the surface. Moreover, they should evaporate quickly and not leave any residue themselves. It is central that the removers not be applied directly to the surface, since they are also good penetrants. Spraying or flushing the specimen with the solvent during the removal step is prohibited by many specifications. When using the visible color penetrants, a slight trace of color on the cloth or paper towel indicates that the removal is adequate. For fluorescent penetrants, slight traces of the fluorescent observed under the black light indicate the adequate level of removal.

Application of Penetrant and Developer



1. Penetrant is applied to the surface and seeps into the discontinuity

2. Penetrant is removed from surface, but the discontinuity remains full

3. Developer is applied to the surface and acts as a blotter to draw the penetrant out of discontinuity producing a visible indication of the defect

Figure 137 The steps of penetrant and developer application [190]

Developers have been described as chalk particles, mainly because of their white and chalk-line appearance. There are four basic types of developers: dry developers (form a), wet developers suspended in water (form b) and the ones that are soluble in water (form c), solvent-based (also known as spirit or non-aqueous - form d for fluorescent PT and 'e' for visible PT). In addition, there are other types of developers that are used occasionally. These are referred to as strippable, plastic film, or lacquer developers. They are typically non-aqueous suspensions containing a resin dissolved in the solvent carrier. Such a developer sets up after application and it is then stripped off the surface with indications in place. The strips can be stored as part of the inspection account. After the part has been inspected, all the traces of any remaining penetrant and developer must be thoroughly removed from the specimen surface prior to it being placed into service or returned for further processing.

6.8.2 Tools and Techniques

Following is a brief overview of the application of the whole technique: First, surface of the specimen is carefully and properly cleaned. Then, a colored or fluorescent dye is applied to a clean surface and allowed to dwell for 10 to 20 minutes and, is drawn into the discontinuity by capillary pressure. Afterwards, the excess dye is removed from the surface and a developer applied. After the excess dye removal, developer is applied which has two functions to assist in drawing the dye back out to the surface, giving an indication to assist in seeing this indication by giving good visual contrast. After a time, usually a minimum of 10 minutes, the surfaces are visually inspected. Eventually, the specimen is again cleaned so that no foreign material remains on its surface.

PT tools and equipment varies from highly portable kits containing aerosol cans to complex in-line test systems such as large high-speed stationary units and highly specialized units for testing of particular objects. The portable kits contain pressurized cans of penetrants, cleaners, removers, solvents and developers, and in some cases brushes, swabs, cloths and a suitable set of instructions. When fluorescent dye penetrant is supplied a small portable UV lamp may also be included. These kits are used when inspections are to be conducted in remote areas in the field or for a small area of a test surface. Small general-purpose, stationary units are completely self-contained.

Equipment consists of a basket for dipping a number of small parts, plus, a drain area is usually located next to the penetrant tank so that the parts can sit until the proper dwell time has elapsed. A rinse tank is provided with UV light for monitoring the rinsing operation and a drying cabinet with circulating hot air is mounted near the rinse tank. A developer tank and an inspection table with a hood and second UV light complete the design. If a post-emulsifiable penetrant is to be used the unit will have an additional tank that contains an emulsifier which renders the surface penetrant removable after a specified emulsification time. The stationary units range from a manually operated penetrant line to very expensive automated lines, in which most steps are performed automatically. The automated stationary or mobile units vary from small and simple systems to very complex lines that are computer controlled. Nevertheless, even with employment of highly automated systems the examinations still have to be conducted by well-trained inspectors [264], [438].

A Stationary Fluorescent PT Unit

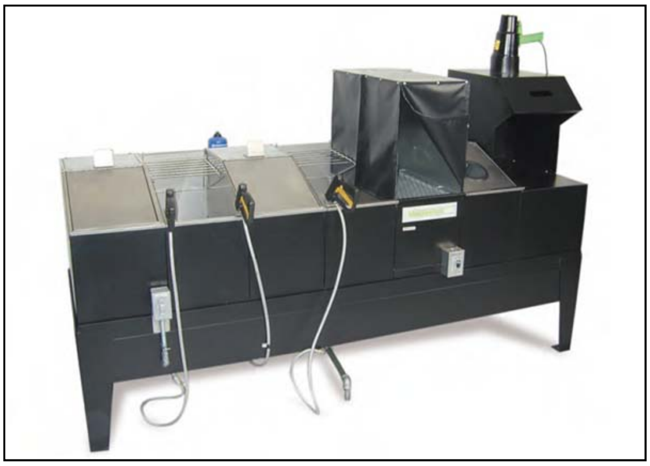
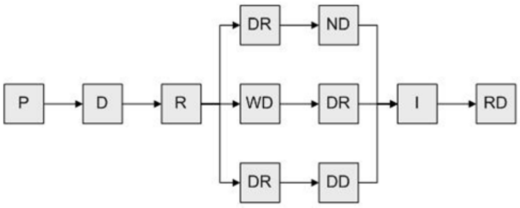
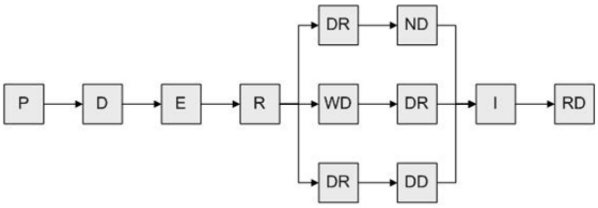
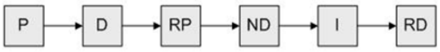
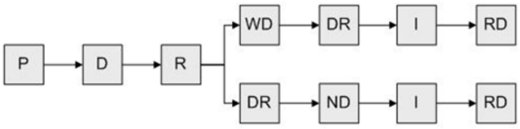
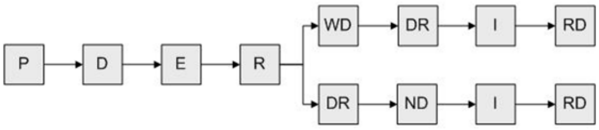
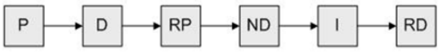


Figure 138 A typical stationary fluorescent PT unit [WS62]

Table 35 shows the flow diagrams of fluorescent and visible penetrant testing procedures. It is necessary to underline that for any of the fluorescent inspection methods the inspection area should be as dark as possible to be able to identify small flaws. Besides, extreme care must be taken to avoid contaminating the inspection area with penetrant in not to face with false indications.

Table 35 Flow diagrams of implication procedures of different PT techniques [80]

Type	Method/Process	Procedure
Fluorescent Penetrant (**I**)	Water Washable (**A**)	
	Post Emulsifiable (**B**/**D**)	
	Solvent Removable (**C**)	
Visible Penetrant (**II**)	Water Washable (**A**)	
	Post Emulsifiable (**B**)	
	Solvent Removable (**C**)	
D: Drain, **DD**: Dry Developer, **E**: Emulsify, **I**: Inspect, **ND**: Non-aqueous Developer, **P**: Penetrant, **R**: Rinse, **RD**: Remove Developer, **RP**: Remove Penetrant, **WD**: Wet Developer		

6.8.3 Use and Applicability

Penetrant testing is very multipurpose and has many applications. It is employed in virtually every major industry and for a wide variety of machinery components or product forms. Industries that widely use PT include: power generation, petrochemical, marine/shipbuilding, automotive, metalworking, aerospace and virtually all various welding processes and metals-joining industries [264]. As Lancha et al. state, some proven applications for PT include inspection of: tools and dies, tanks, vessels, reactors, pipes, dryers, pumps, parts of diesel locomotives/trucks/busses (e.g. axles, wheels, gears, crankshafts, cylinder blocks, connecting rods, cylinders, transmissions and frames), field drilling rigs, drill rope, castings, parts of aircraft engine, propellers and wing fittings [359].

Indications of Discontinuities by Penetrant Testing

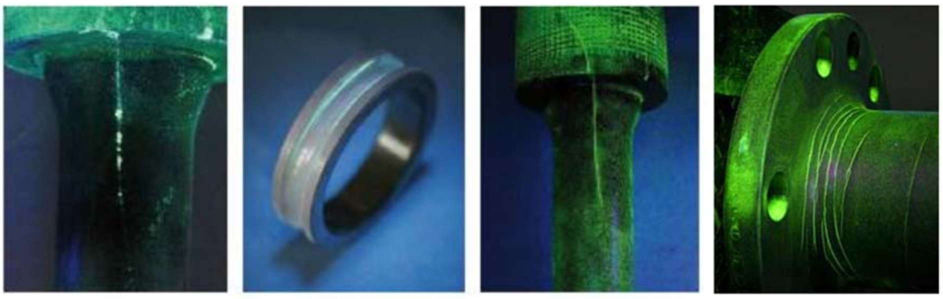


Figure 139 Various indications of discontinuities provided by fluorescent penetrant testing [WS24]

Table 36 Some detectable discontinuities and their indications by penetrant testing [438]

Discontinuity Type	Indication Description
Cracks	Straight or jagged continuous surface lines
Hot tears	Ragged line of variable width, numerous branches
Rolling lap	Continuous line on rolled bar stock
Fatigue cracks	Continuous lines in parts that have been in service
Porosity (glass)	Spherical surface indications
Forging lap (Al)	Sharp crescent-shaped indication on aluminum
Forging lap (other)	An intermittent line indication
Casting porosity	Spherical surface indications
Crater crack (Al)	Dish-shaped indication with spoke propagation
Crater crack (deep)	Rounded indication
Heat-treat crack	Multiple irregular lines in finished goods
Inclusion (rolling)	Broad elongated indications in rolled plate
Casting cold shut	Dotted or smooth continuous lines
Laminations (rolling)	Seams on rolled plate
Thermal crack (glass)	Jagged interconnecting lines fired ceramics
Lack of fusion (welds)	Broken line of varying width near centerline
Sand casting shrinkage	Crack indications where part thickness changes

It is essential to highlight that penetrant testing only detects defects which break the surface, hence, it is primarily used for locating cracks and other flaws that are open to the surface in austenitic stainless steel, aluminum and other materials that cannot be magnetized. PT can also be performed on ferromagnetic metals but is not as efficient as the magnetic particle test. However, penetrant testing is still less dependent on the specimen's material (e.g. in comparison with magnetic particle testing) but oxide layers or other contamination on the surface will affect the quality of inspection. Besides, the material compatibility of the penetrant and cleaners has to be always taken into account and assessed.

Penetrant testing is suitable for materials such as steel, aluminum, copper, plastic, ceramics and castings (i.e. nonporous materials). Some materials (e.g. penetrants, developers and etc.) that are used for PT can cope with temperatures ranging from –15°C to +200°C and trace defects right down to a few microns without ruining the material or the environment.

Applications of Penetrant Testing

Figure 140 From left to right: crack identification in an extrusion ring on the suspicious area which was previously inspected by ultrasonic testing, inspection of welds on two different vessels [WS14]

PT has also a unique application in detection of through-wall leaks. For this purpose, penetrant is applied to one surface, for instance, a tank and developer applied to the other surface. If there is an unhindered through leak, the penetrant will follow that pathway and be exposed on the other developed surface as an indication. Some leak tests, such as those for complex components and piping systems that must be assessed and examined to determine the source and location of a leak path, are conducted using fluorescent tracers. Consideration of the defect parameters is important in selecting the appropriate nondestructive test to use and then in ensuring that it is applied correctly. Penetrant testing is particularly sensitive to round defects whilst magnetic particle testing, for example, is well suited to cracks and linear discontinuities. Besides, PT with colored chemicals provides the most reliable results when all types of surface breaking flaws have to be detected.

Fluorescent dyes give a high contrast ratio that should make indications easier to see but they do not always give the maximum chance of discontinuity detection. For instance, they are not suitable for components with rough or poor surface finishes as it is difficult to remove the excess dye (except Method A), causing an overall fluorescence that masks discontinuities, preventing their detection. They do however make seeing indications in internal bores, cored holes, etc. easier [32], [88]. The below table provides some more detailed information on application of different PT types and processes.

Table 37 Some information on application of different PT types and processes [264]

PT Type - Method	Application
Type I - Method A	▪ For inspection of large surface areas ▪ For inspection of large number of parts ▪ For inspection of parts with complex configurations (e.g. threads, keyways and etc.) ▪ For identification of discontinuities that are not broad or shallow (anticipated defects) ▪ For inspection of parts with rough surfaces (e.g. with sand castings or as-welded conditions)
Type I - Method B/D	▪ For inspection of large number of parts ▪ For application that require higher sensitivity ▪ For detection of inter-granular corrosion or stress cracks ▪ For identification of small defects such as grinding cracks ▪ For identification of discontinuities that are broad or shallow (anticipated defects)
Type I - Method C	▪ For applications in which a heat source is not readily available for drying ▪ For applications in which water removal is not desirable due to part size, surface condition, etc.
Type II - Method A	▪ For inspection of large surface areas ▪ For inspection of large number of parts ▪ For identification of discontinuities that are generally tight ▪ For inspection of the parts with rough surfaces to some extent ▪ For inspection of parts with threads, keyways and other complex geometries
Type II - Method B	▪ For inspection of large number of parts ▪ For identification of discontinuities that are broad or shallow (anticipation) ▪ For inspection requiring lower sensitivity achievable with all Type I methods
Type II - Method C	▪ For inspections that are to be undertaken in a remote location ▪ For field use whenever water removal is not feasible for any reason

6.8.4 Limitations and Pros

As penetrant testing is always an alternative to magnetic particle testing it is vital to express that if applied correctly, both penetrant testing (MT) and magnetic particle testing (MT) can be sensitive to surface discontinuities. However, when the component is magnetic and both tests can be employed, the application of MT is usually preferred to that of PT for number of reasons. MT has the capability to detect discontinuities through thin coatings. PT is less tolerant of poor surface condition and it effectiveness can be highly affected by any material within a defect. In addition MT is much quicker to be used than PT. On the other hand, for nonmagnetic materials, PT is generally used.

Nevertheless, based on the study of Kauppinen and Sillanpaa, penetrant testing associates with 70% detection rate for defects 2mm deep rising to 92% for defects 5mm deep; these percentages for MT are 57% and 93% accordingly [316]. The same study shows that PT associates with 60% detection for defects 10mm long rising to 59% for the ones 50mm long while these percentages for MT are 44% and 59% accordingly. Hence, it can be concluded that in general penetrant testing is more reliable when used for the same purpose and on nonporous materials in comparison with MT.

Specimen geometry can affect both PT and MT inspections. Sudden small changes in section such as weld toes and caps or threads in threaded components can lead to spurious indications. Both tests require the flow of penetrant or particles over the surface and it is necessary to ensure an even distribution over the inspection zone for the required time to allow indications to be produced. The geometry and orientation of the component may interfere with this distribution. In case of PT, the geometry and orientation of the component may mean that the penetrant may collect in certain areas and flow away from others. Similar problems with geometry can be encountered when trying to remove excess penetrant from the component. Particular geometries may determine the technique to be applied e.g. water washable penetrant is generally used on threaded components. All in all, the method used should address these issues to ensure a reliable inspection [32].

Table 38 Pros and limitations of different PT methods [32], [264], [438]

PT Type - Method	Comparative Pros	Comparative Limitations
Type I - Method A	▪ Portable ▪ Relatively cheap ▪ High rate of inspection ▪ High visibility of indications ▪ Inspection of complex geometries ▪ Relatively useable on rough surfaces	▪ UV/Black light required ▪ Relatively lower sensitivity ▪ Unsuitable for retesting of parts ▪ Unsuitable for identification of shallow defects
Type I - Method B/D	▪ High rate of inspection ▪ High sensitivity of testing ▪ High visibility of indications ▪ Suitable for retesting of parts ▪ Suitable for identification of shallow defects	▪ Relatively expensive ▪ Rinsing aid required ▪ UV/Black light required ▪ Unsuitable for rough surfaces
Type I - Method C	▪ High rate of inspection ▪ No need for heat as drier ▪ High visibility of indications ▪ Good for inspection of large parts	▪ Solvent required ▪ Moderately expensive ▪ UV/Black light required
Type II - Method A	▪ Portable ▪ Relatively cheap ▪ Suitable for inspection of large parts ▪ Relatively useable on rough surfaces ▪ Suitable for check-up of contaminated parts	▪ Rinsing aid required ▪ Low rate of inspection ▪ High manpower required ▪ Relatively lower sensitivity ▪ Unsuitable for identification of shallow defects
Type II - Method B	▪ Moderate sensitivity of testing ▪ Suitable for identification of shallow defects	▪ Relatively expensive ▪ High manpower required
Type II - Method C	▪ Portable ▪ Suitable for retesting of parts ▪ Good for inspection of large parts ▪ Suitable for inspections in remote locations	▪ Solvent required ▪ Moderately expensive ▪ Low rate of inspection ▪ High manpower required ▪ Unsuitable for inspection of rough surfaces ▪ Unsuitable for identification of shallow defects

Table 39 Synopsis of liquid penetrant testing

Pros	▪ Portable ▪ Inexpensive ▪ Immediate results ▪ Minimum skill required ▪ Relatively easy to perform ▪ Sensitive to small discontinuities ▪ Effective for production inspection ▪ Direct visualization of discontinuities ▪ Applicable to objects with complex geometry ▪ Relatively fast (i.e. usually requires 30 min or less to accomplish) ▪ Versatile: virtually any solid nonporous material can be inspected	
Limitations	▪ Locate only surface defects ▪ Object preparation required ▪ The process is usually messy ▪ Difficult interpretation of indications ▪ Care required in surface preparation ▪ High level of object cleanliness required ▪ Direct visual recognition of results required ▪ Rough or porous surfaces interfere with test ▪ Temperature variation affects the test result ▪ Usually useful for small to medium size objects ▪ Surface condition and configuration affect the test result	
Equipment	▪ Portable kits to large and complex test units: cans of penetrant, cleaner/remover, solvent and developer, brushes, swabs, cloths, white/black lights and driers	
Discontinuity types	▪ Void ▪ Seam ▪ Crack ▪ Pitting ▪ Erosion ▪ Fatigue ▪ Porosity ▪ Hot tear ▪ Inclusion ▪ Corrosion ▪ Cold shut	▪ Shrinkage ▪ Rolling lap ▪ Forging lap ▪ Lamination ▪ Crater crack ▪ Stress crack ▪ Fatigue crack ▪ Thermal crack ▪ Corrosion crack ▪ Surface-breaking
Discontinuities size	▪ Practically useful to detect discontinuities with depth of 0.4 mm or more	
Relative inspection cost	▪ It is relatively cheap: A type II PT portable kit approximately costs 50 € while this price for a type II kit ranges from 400 € to 600 €. A stationary testing unit costs from 5,000 € to 10,000 €. ▪ Relative minimal expense combined with large savings opportunities will most result in a very short equipment payback period.	

6.9 Radiographic Testing

Traditionally, industrial radiography, radiographic testing (RT), is the next most common NDT method after visual and optical inspection in different industries and for variety of applications. Significant activity in the field occurred almost immediately after Roentgen's discovery of x-rays in 1895 [90]. Early literature notes the ability of radiographs to detect discontinuities in castings, forgings, and welds in metals. Discontinuities such as pores or inclusions in metals are readily detected in many cases. Cracks may also be detected using radiographic techniques, but attention must be paid to orientation and residual stress issues. Radiography continues to be widely used despite the expense and safety implications of the equipment. Recent advances in digital radiography have helped reduce the cost of employing this method by eliminating the use of film [204].

6.9.1 Conception

Radiographic testing inspects materials for hidden flaws by using the ability of short wavelength electromagnetic radiation (i.e. high energy photons) to penetrate various materials. RT employs ionizing electromagnetic radiation to view objects in a manner that reveals its hidden flaws and defects. The testing technique is based on differential absorption of radiation by the part under inspection. The source of radiation can be from radioactive sources, typically Irridium-192, Cobalt-60 and Caesium-137, which emit gamma-rays or from a specially built machine that can emit x-rays. Commonly, the former is known as gamma radiography whereas the latter is referred as x-ray radiography [296].

RT uses x-rays, gamma-rays or even neutrons and electrons to produce a graphical schematic of a specimen showing any changes in thickness, defects, and assembly details to ensure optimum quality in operation. However, defects such as delaminations and planar cracks are difficult to be identified by RT; hence, penetrants are often used to enhance the contrast in the detection of such defects. Penetrants used include silver nitrate, zinc iodide, chloroform and diiodomethane. Choice of the penetrant is determined by the ease with which it can penetrate the cracks and also with which it can be removed [33].

As mentioned above, two types of electromagnetic radiation are used to perform radiographic inspection: x-rays and gamma rays. The primary distinguishing characteristic between these two types of radiation is the different wavelengths of the electromagnetic energy. Compared to other types of radiation both X-rays and gamma rays have relatively short wavelengths which allows them to penetrate opaque materials. This inherent capability is what enables their use for nondestructive testing, as they can reveal flaws embedded in visually non-transparent materials [80].

The Electromagnetic Spectrum

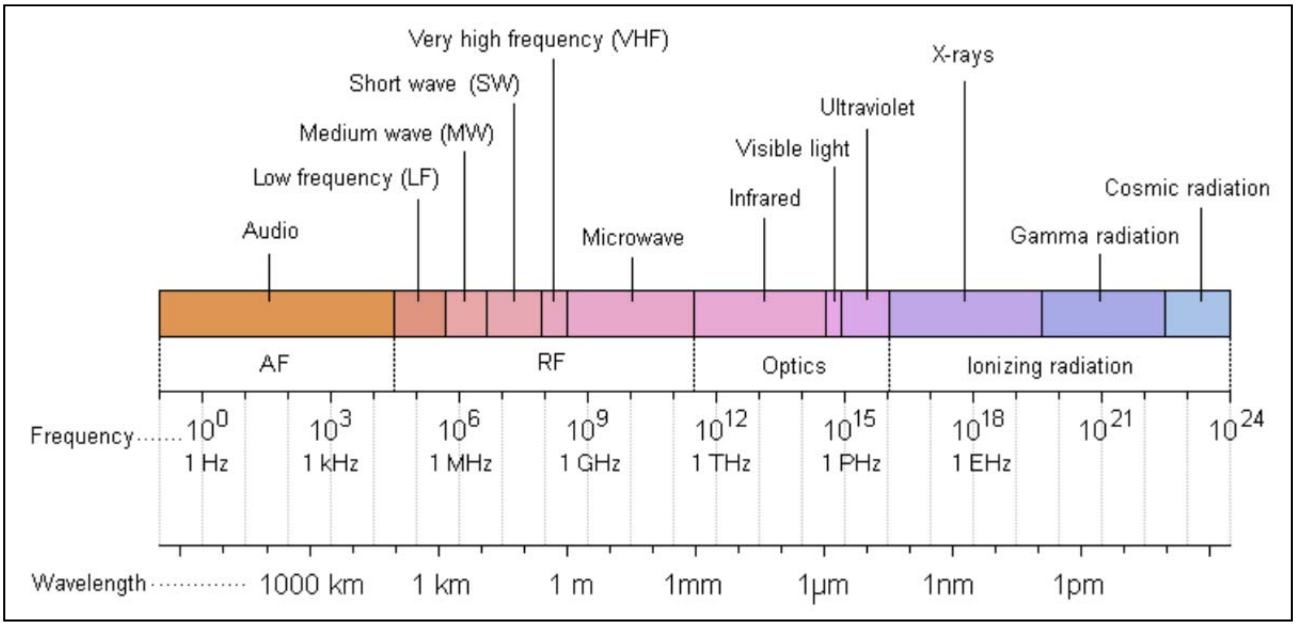


Figure141 The electromagnetic spectrum and the corresponding spots of x-rays and gamma-rays [WS106]

Basically, RT involves the projection and penetration of radiation energy through the specimen being inspected. Ingold explains that the radiation energy is absorbed uniformly by the material or component being inspected except where variations in thickness or density occur [293]. The energy not absorbed is passed through to a sensing medium that captures a photographic record of the radiation pattern known as the radiograph. The uniform absorption and any deviations in uniformity are subsequently captured on the radiograph and indicate the potential presence of a discontinuity.

Discontinuities such as cracks, slag inclusions, porosity, lack of penetration and lack of fusion reduce the effective thickness of the material under test. Thus, the presence of such discontinuities causes radiations to experience less absorption as compared with those in areas with discontinuity. As a result, in areas containing discontinuities more radiations escape, recorded by the radiograph and forming a contrastive indication that represents the internal structure of the material.

The appearance of radiographs depends on the type of discontinuities stumbled upon by the radiation. Cracks for example will produce a fine, dark and irregular line, whereas porosities produce dark round indications of different sizes. Some discontinuities existing in other materials such as tungsten inclusions in steel have higher density than their surroundings. In this case, the effective thickness that needs to be traversed by radiation is somewhat greater. In other words, more radiation is absorbed in such areas as compared with others. As a result the intensity of radiation that escaped after traversing this area is less than that for other areas generating a lighter indication bearing the shape of tungsten inclusion inside the material [296].

There are different techniques that facilitate radiographic testing and form a variety of methods; the most central ones, which are more frequently used for industrial purposes, can be listed as: Film Radiography (FR), Digital Radiography (DR), Computed Radiography (CR), Computed Tomography (CT), Neutron Radiography (NR), Neutron Radioscopy (NS) and Neutron Tomography (NT) [111], [470], [632]. These radiographic testing methods are explained briefly in this section.

1. *Film Radiography:* This method, abbreviated as FR, involves projection of an x-ray or gamma ray which penetrates through the specimen under inspection. While traversing through the material, these radiations experience modification by the internal structure of the material through absorption and scattering processes. If the internal structure is homogeneous, the absorption and scattering processes would be uniform throughout the material and radiations that escape from the material would be of uniform intensities. The energy not homogeneously absorbed is passed through to a sensing medium capturing an image of the radiation pattern.

   The uniform absorption and any deviations in uniformity are captured on a radiographic film which later may indicate the existence of a flaw or discontinuity. Afterwards, the film or cassette is taken to a darkroom where the film is placed in an automatic processor or being processed manually. When the film is processed, a uniform dark image will appear on the film that denotes the homogeneity of the material tested. The situation is different for cases of materials containing discontinuities or different in thickness (i.e. they are shown by a range of grey colors). In general, the absorption of radiation by a material depends on the effective thickness (i.e. width or depth of material) through which the radiations penetrate [190], [249].

   In manual film processing, the development process begins after the film is exposed to the radiation and an invisible change called a latent image develops on the film emulsion. These exposed areas become dark when the film is placed in a developing solution. The degree of darkening that occurs during this process depends on the amount of exposure that occurred. The next step is to place the film into a special bath and rinse it to stop the development process. Lastly, the film is put into a fixing bath and then washed to remove the fixer solution. At this point the film is fully developed, the process is completed by drying, and the radiograph is then ready to be handled and analyzed. Through the processing, proper control of the temperature and time of the development process is of significant importance [494].

FR Test Setup

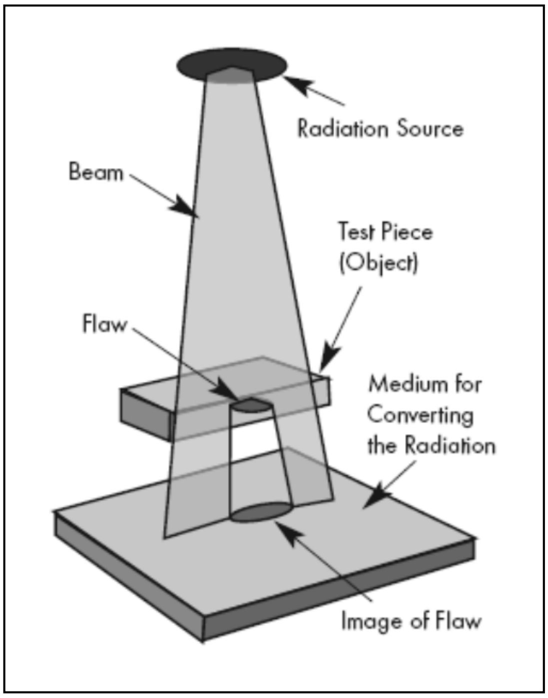


Figure 142 Fundamentals of a FR exposure and the typical test configuration [293]

2. *Digital Radiography:* This method, abbreviated as DR and also known as real-time or direct radiography, is a radiographic test in which penetrating radiation (i.e. x or gamma ray) is passed through a specimen in order to generate an image on a screen, where the image is viewed in concurrent irradiation. Indeed, after exposure, a digital radiography system will almost instantly display the image on the display in front of the technician, therefore eliminating any need for processing. It is notable that in DR less radiation can be used to produce an image of similar contrast to conventional film and computed radiography.

   It is also crucial to underline that the term digital radiography is restricted to flat, two dimensional radiographic imaging; Computed tomography, on the other hand, involves more advance forms of three dimensional computed images. Image processing or enhancement can of course be performed on DR images in the same way that CR images can due to the digital format of each. There are many different types of DR detectors in use in industry. Each type has its own merits and distinctions and may be applied to certain imaging requirements based on these attributes. Harara generally categorizes the DR detectors into the following three major groups [253]:

   (1) Indirect conversion charge-coupled detector, which is used as the image-acquisition component of cameras in video and digital photography. This detector is composed of an x-ray scintillator, lenses and charge coupled detectors (CCDs) to capture the image of the light emitted by the scintillator.

   (2) Indirect conversion flat-panel detector that is composed from x-ray scintillator, photodiode and thin film transistors (TFT). TFT is an electronic switch made from amorphous silicon on flat-panel detector, and allows the charge collected at each pixel to be independently transferred to an electronic circuit where it is amplified by photomultiplier to be then converted from analog to digital in order to produce the digital image data. The digital image is then processed to produce the suitable image for display and diagnosis.

   (3) Direct conversion flat-panel detector, also known as digital detector array (DDA), is composed of an x-ray photoconductor (i.e. made from amorphous Selenium) and a TFT in such a way to become more efficient by eliminating the need for intermediate steps or additional conversion processes for producing the digital image. Digital radiography systems which have integrated DDAs are more suitable for in-house inspection, because they require stabilized temperature and moisture conditions [113], [185], [250].

Table 40 Suitability of FR and DR in detection of different discontinuities in metals [293]

Discontinuity/Problem Type	X-Ray Film Radiography	Gamma-Ray Film Radiography	Digital Radiography
General			
Void	++	++	++
Thickness	+	+	++
Internal crack	++	++	++
Surface crack	++	++	++
Metallurgical variations	+	+	+
In Welds			
Pore	++	++	++
Slag inclusion	++	++	++
Shrinkage crack	++	++	++
Incomplete fusion	++	++	++
Incomplete penetration	++	++	++
In Service			
Fatigue	+	-	+
Thinning	+	+	+
Blistering	-	-	-
Heat crack	+	-	+
Corrosion pitting	+	-	+
Stress corrosion	+	-	+
In Castings			
Void	++	++	++
Pore	++	++	++
Cold shut	++	++	++
Core shift	++	++	++
Surface crack	+	+	+
Internal shrinkage	++	++	++
In Forgings			
Lap	-	-	-
Tear	+	+	+
Crack	+	+	+
Inclusion	+	+	+
Internal burst	++	++	++
Internal flake	-	- -	-
In Processing			
Grinding crack	- -	- -	- -
Heat-treating crack	- -	- -	- -
In Bars and Tubes			
Pipe	-	-	-
Seam	++	++	++
Cupping	++	++	++
Inclusion	+	+	+
In Sheets and Plates			
Void	++	++	++
Thickness	++	++	++
Lamination	- -	- -	- -
Good(++), Average(+), Fair(-), Poor(- -)			

3. ***Computed Radiography:*** This method, abbreviated as CR, employs similar tools to the film radiography except that instead of using a film to generate the image, an environmentally safe imaging plate or cassette is used. It is located under the specimen and then the x-ray (more commonly) or the gamma-ray exposure is made. Afterwards, the cassette is moved through a special laser scanner to read and digitize the image, which can then be viewed and enhanced using software that has functions very similar to other conventional digital image-processing software, such as contrast, brightness, filtration and zoom. In the software, the scanned image is encrypted so that the original data is kept secure and cannot be tampered with. Such cassettes contain photo-stimulable phosphoric elements that hoard the radiation level received at each point in local electron energies. When it is put through the laser scanner, the scanning laser beam causes the electrons to unwind to lower energy levels, emitting light that is detected by a photo-multiplier tube, which is then converted to an electronic signal. Next, the electronic signal is converted to digital values and placed into the image processor pixel map. Cassettes can be reused thousands of times if they are handled carefully. A cassette can be erased by being simply exposed to a room-level fluorescent light [369].

There exist several factors which shove the move away from FR techniques toward CR systems. With CR systems, images are generated on a medium that does not require the chemical bath processing as in FR. Traditional film chemicals must be used within a limited timeframe, which forces processing labs to maintain a fresh stock of chemicals. CR eliminates the cost of procuring and maintaining these supplies. CR's image plate (IP) is typically only 0.5 cm thick and can easily be cut and can be shaped to meet specific imaging needs, plus, theoretically they can be reused up to 5,000 times unlike single use of FR film. There are many consumables purged by using CR such as envelopes, marking pencils, cleaning materials, gloves, and shields, and also several support equipment in addition to the developing tanks and processors, like water chillers, safe lights [369].

In addition to the above factors, CR test operators are not exposed to film processing chemicals and are subjected to significantly less radiation. This contributes to quicker inspection site set-up and allows other work efforts to continue nearby. Moreover, CR image processing times are reduced significantly in comparison with the ones of FR that enables the operator to determine quickly if shots are acceptable or not. The operator can also manipulate the presentation density and inspect a wider range of material thicknesses with a single exposure on a single IP as opposed to taking multiple film shots that use either different exposure times or different film speeds. CR systems allow users to transmit, evaluate, and store images electronically, which makes internet transmission possible and lessens the required storage space [369]. While CR offers several operational advantages over conventional film radiography, it also has its limitations. As with any new technology, it has both a learning curve and an acceptance curve. Moreover, standards for accepting and rejecting inspection results are still being developed. Besides, although many recurring expenses are reduced, some still exist and the up-front costs of CR are substantial. The complexity of CR systems warrants careful consideration on where they will be located.

Table 41 A comparison of the traits of computed radiography and digital radiography

Trait	Radiographic Testing Method	
	Computed Radiography	Digital Radiography
Procedure	Similar to FR, CR needs exposure of the imaging plate which is then moved from the inspection site to the reader location. The CR plate is digitized and then the image is evaluated on the PC. The plate is then erased. If a reshoot is required, the imaging plate is returned to the inspection site for another exposure.	DR needs exposure of the digital panel. Images are then immediately available on the PC without moving the panel from the inspection site. If a reshoot is required, everything is set for a new exposure. In DR scanning systems, images can be viewed and evaluated as they are being exposed in real-time.
Resolution	The resolution at which the CR imaging plates are read is selectable. The highest currently available resolution with CR is 50 μm. The tradeoff is that the higher the resolution, more exposure and read time required. At resolution of 100 μm, time between 1 and 5 minutes is required to digitize the image, plus, another 0.5 to 2 minutes to erase the imaging plate.	The highest currently available resolution at which the DR panel captures is 48 μm. At this resolution, the time to acquire the image is 12 seconds on average.
Portability	CR imaging plates are very portable. This method excels when the technician must access difficult-to-reach locations where a DR cable would be cumbersome or impractical to manage, or where it is necessary to match the imaging plate to a curved surface. The typical CR reader/eraser is not portable although there are some portable systems in the market as well.	DR panel can be field portable depending on its size. DR workstation can be also portable in case of use of laptop instead of a PC. Some complete DR systems can be moved to the inspection site, the power source of which can be provided by large batteries.
Swiftness	Similar to FR, CR process has multiple steps. Turnaround time from image to image with CR is typically between 2 and 10 minutes or even more, accounting for the time taking the imaging plate to the reader, reading, erasing, and returning it to the inspection site.	DR is able to provide images within a few seconds. Typically, the turnaround time from image to image is between 5 and 20 seconds.
Usability	Similar to FR, the multi-step process for using CR is too slow for most production applications; however, this does not hold for maintenance purposes.	DR can endow with continuous inspection of hundreds or even thousands of parts per hour. This makes DR a suitable choice for production and quality control applications. Some DR equipment may have an automatic defect recognition (ADR) system as well.
Potency	CR outrivals for field operations where access is limited or the imaging plate must conform to the object shape. Plus, CR is usually the best choice for use with isotopic sources.	DR outrivals for production applications where higher speed and/or imaging quality are required. Moreover, Portable DR systems can provide immediate results in field applications.
Cost	Some CR systems have built-in reader/eraser workstations while some require their purchase. They need a connected PC, display and software, plus, a supply imaging plates. An average total initial cost of a complete CR system is around 75,000 €. The imaging plates have to be replaced whenever damage which brings an additional cost of 300 € - 800 €.	A typical DR system includes imaging panel, connecting cables, PC, display and software. The average total cost for such a system varies between 80,000 € and 120,000 € depending on the technology used and the size of its imaging panel. However, there is no extra cost for consumables.

4. ***Computed Tomography:*** This method (CT) is another important RT technique with enhanced flaw detection and location capabilities. Unlike FR and DR, CT involves the generation of cross-sectional views instead of a planar projection. The CT image is comparable to that obtained by making a radiograph of a physically sectioned thin planar slab from an object. This cross-sectional image is not obscured by overlying and underlying structures and is highly sensitive to small differences in relative density. Therefore, characteristics of the internal structure of the specimen such as dimensions, shape, internal defects and density are readily available from CT images. Computed tomography images are also easier to interpret than radiographs.

   However, as with any radiographic method, CT image quality is an essential concern as the ability to reliably detect flaws and structural discontinuities within the component highly depends on the quality of the generated images. The main parameters used when considering image quality can be underlined as: Image contrast, which is the ability of an imaging procedure to reliably depict very subtle differences in contrast. Spatial resolution that is the ability to discriminate between adjacent objects; it is a function of pixel size. Image noise which is mainly caused by the quantum structure of the x-ray beam and is an important determinant of CT image quality as it limits the visibility of low-contrast structures. And eventually, artifacts that are denoting the appearance of details in a CT image not actually presented in the scanned specimen.

   The process of image reconstruction in computer tomography is consisted of three phases. First is the scan phase; CT machines use various methods of acquiring basic projection data to produce a CT image. These methods are classified in terms of their scan geometry about the specimen. For instance, 2nd generation CT systems are usually used which operate a translate/rotate scan geometry about the object, whereas most industrial systems use a 3rd generation configuration that involves the use of cone beam projections. The specimen under study is placed on a rotating manipulator, which enables the system to collect various angles of x-ray attenuation data or x-ray projections needed to perform CT reconstruction. Second is the main image reconstruction phase in which complicated algorithms are used to reconstruct a 2D digital image from the set of x-ray projections (i.e. sinograms) created during the scan phase. The most common algorithm used for this process is the filtered back projection method that calculates from a set of 1D sinogram lines a reconstructed 2D image.

   At this point, the CT image is digital in the form of a matrix of pixels. Another part of the reconstruction process is the calculation of CT numbers for each image pixel. CT numbers are calculated from the x-ray attenuation data for each individual voxel (i.e. volumetric pixel). In fact the, x-ray attenuation depends on both density and atomic number of materials as well as the energy of the x-ray photons. Hence, it is the density of materials that determines the CT numbers; thus, the CT image can be considered as an image of the densities of the materials. Third is the phase of visible image formation in which the digital image consisting of a matrix of pixels with each one having an assigned CT number is converted into a visible image represented by different shades of grey. Each CT number represents a shade of grey with +1000 characterizing white and -1000 signifying black at either end of the spectrum.

CT Test Setup

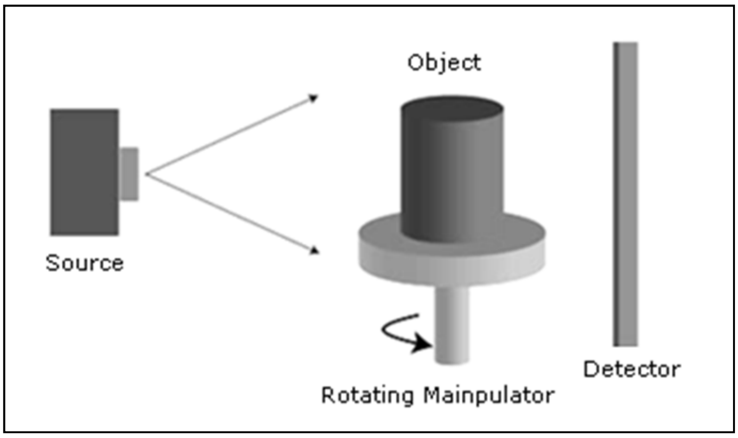


Figure 143 The fundamentals of a CT exposure and the typical test setup [WS99]

5. *Neutron Radiography:* This technique, known as NR, is a radiographic imaging technique which provides images similar to the ones of FR. In fact, neutron is one of the constituent nucleons of the atomic nucleus (i.e. the other is the proton) that has zero electric charge, but a magnetic moment and its mass is about 1840 times that of the electron. Outside the nucleus a free neutron will decay into a proton, electron, and antineutrino with a lifetime of about 15 minutes. Neutron can be described as a classical particle with a particular mass but it shows wave character as well, which can be described with the de Broglie wave length. Neutrons, in particular those traveling at very low velocities (i.e. thermal neutrons), are absorbed in matter according to laws that are very different from those that govern the absorption of x-rays and gamma rays.

   To illustrate, as neutron is electrically neutral, it interacts only weakly with matter into which it can penetrate deeply; contrary to x-rays, which interact dominantly with the electron shell of the atom, the neutron does on the level of the nucleus. As a result, photographic materials are very insensitive to the direct action of neutrons and, if neutrons are to be used for imaging, some method must be used to convert their energy into a form more readily detectable photographically. Elements having adjacent atomic numbers can have widely different absorptions, and some low atomic number elements attenuate a beam of thermal neutrons more strongly than some high atomic number elements. For instance, hydrogen has much higher neutron attenuation than does lead; as a consequence, the height of the water in a lead standpipe can be determined by neutron radiography, which is impossible with x-ray or gamma-ray radiography [494].

   NR aims at the detection of transmission differences in specimens. These might be caused by missing material (e.g. pores or cracks) or inclusion of material showing alternative transmission behavior. The transmission differences of such defects depend on their size and isotopic composition. Their detectability is additionally determined by the characteristics of the neutron source and collimator together with sensitivity of the detector system. NR detectors are generally plane integrating position-sensitive imaging devices containing material with a high neutron cross-section functioning as neutron converter and a recorder, which has the task of collecting the signal emitted by the converter during exposure. Such detectors are able to measure the neutron field in two dimensions perpendicular to the beam direction. Therefore, the detector area should be in the order or larger than the beam cross section. After the measurement, the detector signal is read out and may be digitized. In the context of the neutron radiographic measurement the output of the detector will be called detector signal or radiographic image, whereas the terms signal and image are considered equivalent.

   The difference between neutron and x-ray or gamma-ray interaction mechanisms produces significantly different and often complementary information. For instance, while x-ray attenuation is directly dependent on atomic number, neutrons are efficiently attenuated by only a few specific elements. In fact, while penetrating matter x-rays interact with the electron clouds of the atoms in the object. Hence, the attenuation of x-rays depends on the charge density of the electron cloud and increases with the atomic number of the sample material, respectively. Unlike X-rays, neutrons interact with the nuclei. For this reason, the total neutron cross-section subject to the neutron energy depends on the properties of the nuclei and its size varies from element to element, even from isotope to isotope.

   Essentially, organic materials or water are clearly visible in neutron radiographs because of their high hydrogen content, while many structural materials such as aluminum or steel are nearly transparent. The figure in the next page represents two images taken from the same object with x-ray and neutron radiographic systems. It demonstrates impressively that neutron radiography upshot different information than what obtainable with x-ray as the two methods can visualize different materials. Considering the image on right, as neutrons penetrate the metallic enclosure of the camera easily, plastic components which contain hydrogen inside the camera get able to be seen; whereas in the image on the left, captured using an x-ray radiographic system, mainly the metal parts of the camera are visible.

A Comparison between X-ray and Neutron Radiographic Images

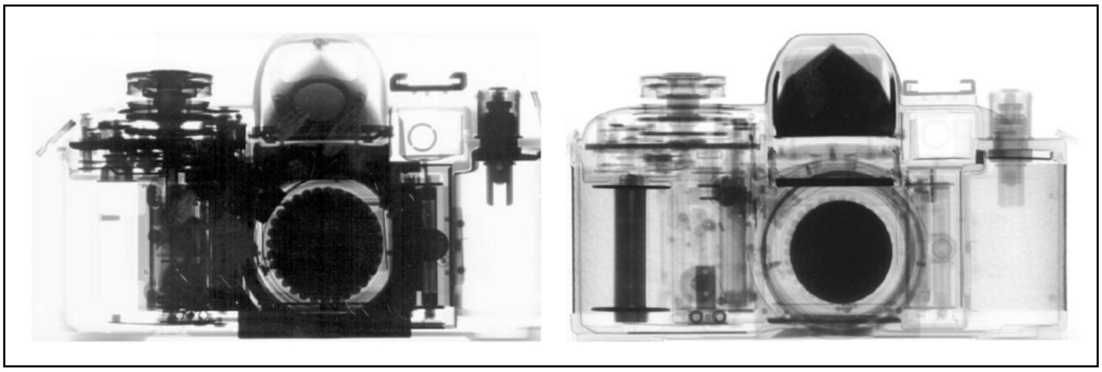


Figure 144 Images taken from a camera using x-ray and neutron radiographic systems from left to right [WS12]

6. *Neutron Radioscopy:* This method, abbreviated as NS, is a dynamic neutron imaging technique which can be someway compared with DR in technique. NS consists of the continuous visualization of the attenuation of a neutron beam using a real-time detector. Whereas NR is imaged on a photographic film, NS uses a scintillator and a video camera. Using this method, the direct examination of dynamic events under neutrons can be observed and the resulting information helps understanding of the dynamic behavior of complex systems. The dramatic improvements of video equipment, cameras and computers have contributed to an emergent development of NS.

   As mentioned above, NS does not make use of film but rather a video camera with screen intensifiers or a charged coupled device camera with a scintillation screen to record the image. There are two phases in the installation of a CCD camera system. The first phase is the assembly of the hardware, which includes the CCD camera, mirror, lens, scintillation screen, and a light-tight enclosure. The second phase is the testing of the CCD camera system to determine its capabilities and performance. Testing of the system includes quantifying the system's resolution, optimizing the exposure time, quantifying the neutron scintillation screen interaction and quantifying the results from taken images. The image which is stored in a digital format on a computer can be reviewed and modified for digital enhancement purposes [372].

NS Test Setup

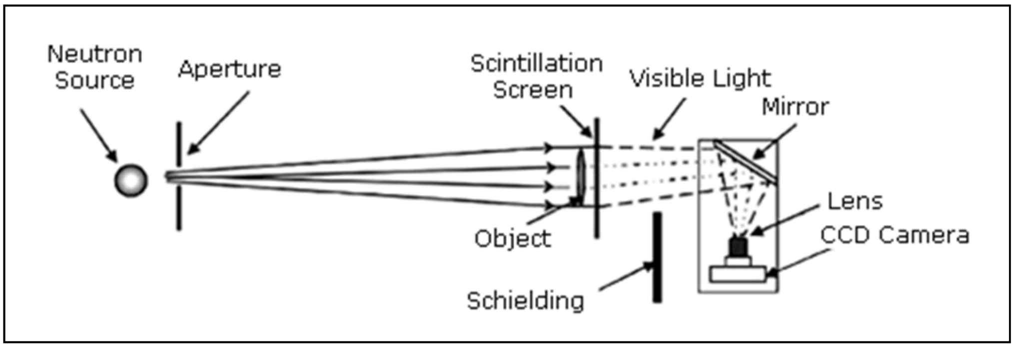


Figure 145 Fundamentals of a NS exposure and test configuration [115]

7. *Neutron Tomography:* Indeed, tomography is a method which provides cross-sectional images of a specimen from transmission data, measured by irradiating it from many different directions. Tomographic imaging in a mathematical sense deals with reconstructing an image from its projections. Here the projection at a given angle represents the integral of the image in the direction specified by that angle. On the other hand, neutrons' unique ability to image certain elements and isotopes that are either completely undetectable or poorly detected by other NDTs makes neutron radiography an important tool for nondestructive inspection. Combining the techniques of tomography and the features of neutron radiography results in development of new RT method named as neutron tomography or NT. Neutron radiography is mostly done taking one or more two-dimensional parallel projections. However, transmission properties of the specimen under inspection can be observed from any sought angle by rotating the specimen in small angular steps over 180° and calculating tomographic slices using computing systems.

Hence, NT is able to provide three-dimensional transmission volume data from a series of two-dimensional parallel projections of a specimen. The provided image is a map of the linear attenuation coefficient averaged over a pixel or voxel size used in reconstruction that visualize physical structures in their actual relative spatial positions and orientations. A typical NT system is consisted of a neutron source, a specimen turntable, a scintillator screen, a mirror, a cooled CCD camera, and computer support. The many times repeated turning of the specimen and acquiring a neutron transmission image is implemented in an automatic procedure connecting a CCD camera with the rotating table and a neutron beam screen. Exposure times in the range from 5 to 60 seconds are imposed by the neutron flux level and the specimen's neutron transmission given by its thickness and isotopic composition [514], [565], [623].

NT Test Setup

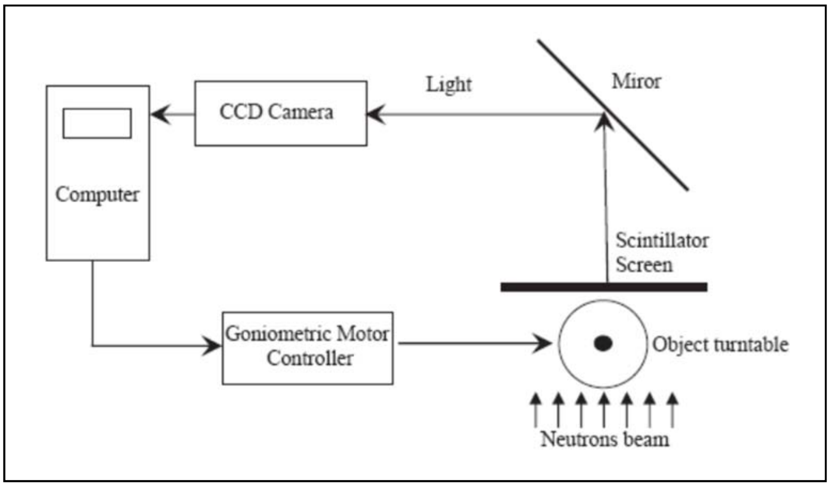


Figure 146 Basics of a NT exposure and the test configuration and procedure [322]

As explained above, NT is a method to obtain plane or volumetric maps of the neutron attenuation coefficient values of a specimen. In that way, the morphology or structure of a specimen can be visualized non-intrusively. Evidently, for that purpose, a series of transmission measurements at a sufficient number of angular views are taken, from which the plane or volumetric maps are reconstructed. The main differences between NT and CT are due to the other radiation matter interaction characteristics of neutrons and x-rays or gamma-rays and their fairly diverse source properties. Such differences bring about complementary information from CT and NT. In recent years, neutron tomography has turned out to be more used for a variety of applications such as nondestructive testing, material design and testing, imaging of rapid processes and so on. This is indeed owing to improvement of spatial resolution and scintillator materials in addition to the availability of digital neutron area detectors and increased power of computers [624], [642].

Latterly, it should be uttered that there are other radiographic methods like electron and proton radiography that have very limited applications in special fields in industry. In electron radiography, electrons emitted by lead foil irradiated by x-rays pass through a thin specimen of low atomic number. They are differentially absorbed in their passage and record the structure specimen on a film. Specimens that can be examined by electron radiography are limited by the range of the electrons to thin, light materials such as papers, wood shavings, leaves, fabrics, and thin sheets of rubber and plastic. Moreover, objects to be examined by this method need to be smooth and plane on at least one side [429], [494]. Although electron and proton radiography are more utilized in scientific fields or for very special purposes, but they have some merits which may bring them to the frequent industrial use in the future. For example, regardless of small number of proton sources available as a shortcoming, unique characteristics upraise potential applications for proton radiography. One of these features is the level of details that are clearly distinguishable in the proton radiographs. This is sometimes in contrast with the conventional x-ray radiographs which may show less details as some areas in the specimen may be overexposed or underexposed [93], [447]. Considering these issues, still, the author does not go through their concepts and related issues as these radiographic methods have almost no industrial application.

6.9.2 Tools and Techniques

Penetrating radiation comprises electromagnetic radiation in the wavelength range below about 1 nm (i.e. approximately equivalent to 1 keV energy) or particle radiation. X-rays are generated electrically in the electronic shell of atoms. Gamma-rays are produced by the natural disintegration of nuclei in a radioactive isotope, Iridium-192 and Cobalt-60 being most commonly used. On the other hand, particle radiation can be produced with particle accelerators, sometimes requiring special targets [49]. For instance, neutrons come from a spallation source or a nuclear reactor while x-rays are generated by electron beam impact on targets in evacuated tubes or in accelerators by Bremsstrahlung, the braking radiation emitted by accelerated charged particles [405], [494]. To illustrate, the figure below provides a picture and a schematic of an x-ray tube. In this type of x-ray tube electrons boil off the cathode when the filament is heated by a current. A high voltage between cathode and anode causes the electrons to accelerate toward the anode, which rotates to avoid overheating of the target. When the electrons strike the anode's target area, x-rays are emitted.

An X-ray Tube

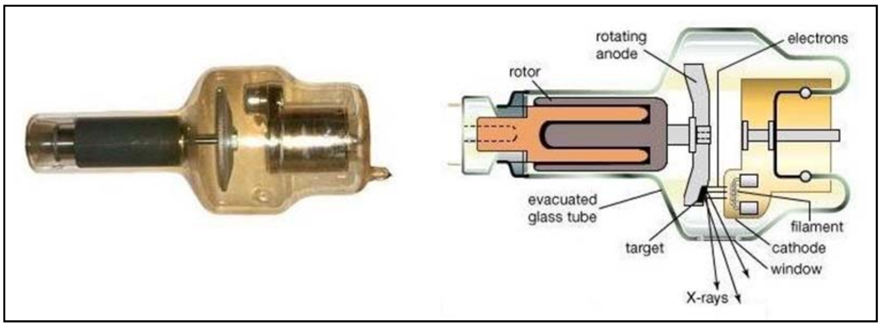


Figure 147 A photo and a schematic of an x-ray tube [WS66], [WS21]

As Hellier explains, industrial x-ray equipment can be classified by energy groups. The x-ray units that generate energies up to 125kV are considered low energy, between 125 and 400 kV are regarded as medium energy and the equipment which produce radiation energies above 400 kV are placed in high energy group [264]. Most of the radiographic inspections undertaken today are done in the medium energy range. Industrial x-ray units are available in different sizes, shapes and duty cycles. There are x-ray units in cabinet, suitable for inspecting smaller parts made of low-density material or with limited thickness. There exist portable x-ray systems with gas filled tube heads that are light weight and appropriate for field use.

Many of the stationary systems are self-rectified and continuous duty but the portable ones with gas filled tubes can operate for a specific time and require time permitted for cool-down required for the next exposure. Coming to industrial gamma-ray equipment, the major component is the exposure device which has a shield that contains an s-tube in which usually the iridium or cobalt source is maintained. The other accessories which may be used in conjunction with x or gamma ray generators in not fully automated systems are: film and cassettes, lead screens, penetrameters (i.e. used as image quality indicators), densitometers, high-intensity film illuminators, processing equipment (manual or automatic), film hangers (i.e. for manual processing) and collimators.

Portable, Mobile, Stationary and Immobile X-ray Systems

Figure 148 A variety of modern industrial x-ray systems [WS44]

The verity that RT is very sensitive to the orientation of the radiation beam with respect to that of the sought flaws and irregularities is commonly acknowledged. This attribute results in a great intricacy in detecting defects such as delamination or disbond. However, this can be resolved by the use of a radio opaque liquid penetrant before exposing the specimen to the radiation beam. This technique is referred to as penetrant enhanced radiography (PER). Although this approach has been very successful in indicating the extent and nature of impact damage especially in composite, it is not widely used. There are a number of reasons for this. Many of penetrant liquids used, having very attractive technical features, have repellent properties from the points of view of health, safety and environment. Most are volatile organic halides and require to be handled with great care to protect operators. Solutions of inorganic halides such as silver nitrate and zinc iodide in an aqueous solution of isopropanol with a little wetting agent have been found to be useful; these, however, lack the attraction of ready volatility. A further drawback of using radio opaque penetrants is that they are very invasive and can pull out well beyond the defective area, giving a forged impression of an extensive defect [386].

To determine the location in depth of a flaw within an object, there are two general techniques, stereo radiography and the parallax method. The merit of stereo radiography lies in providing a vivid 3D view of the specimen, although with the aid of auxiliary procedures it can be used for the actual measurement of depth. The more convenient scheme for depth measurement is the parallax method in which from two exposures made with different positions of the x-ray or gamma-ray tube, the depth of a flaw is computed from the shift of the shadow of the flaw. Although stereo radiography and the parallax method are essentially alike in principle, they are performed differently. In fact, stereo radiography is a RT technique which involves taking two radiographs; one normal to the surface of the specimen and the other at an angle of around 15°, which produces an apparent 3D view of the item. This technique is reported to provide a detailed data of the through thickness of materials and localizing indications of damage. By this method, it is possible to locate a single ply within a laminate [494].

Flash radiography, as another technique, entails exposure times of 20 to 60 ns to overcome the difficulty of high-velocity objects. It has been utilized to record phenomena that occur during rapid dynamic events. These events are difficult to record by other means due to the speed of the event or associated obscurations. To eliminate the motion blur of objects moving at high speeds, it is necessary to have extremely short exposure times. Data capturing is done with various film and high-speed intensifier screens to generate a stopped-in-monitoring negative of the object or the phenomena [362]. The below figure shows its basics: the production of x-ray pulses, their transmission through a test object and their detection. The location of material interfaces (i.e. potential defects) recorded at the detector are blurred because the x-ray source has a finite extent, and electrons knocked into motion by arriving x-rays have a finite range in the detector [148]. Flash radiography has different applications in study or inspection of shaped charges, in-flight dynamics, ballistics, structural phase formations and, rocket and jet motors. Low-voltage flash x-ray systems have the advantage of lower cost, smaller size, portability and better contrast [438], [481].

Basics of Flash X-ray Radiography

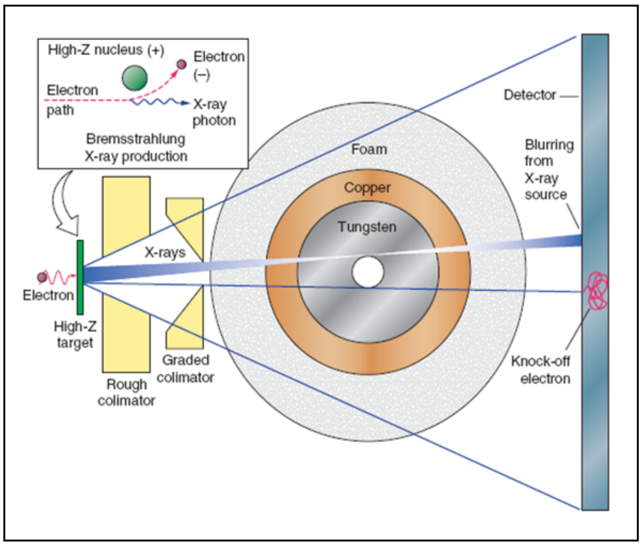


Figure 149 Fundamentals of x-ray flash radiography [148]

While FR employs a film to record the radiographic image, digital radiography is a dedicated electronic system that enables radiographic images of specimens under examination to be generated and displayed on a screen which can be further processed to retrieve more information. A typical DR unit is consisted of five main subsystems: image acquisition system, image storage and retrieval system, display monitor or screen, information process and management system, and image analysis application software. The benefit of this is that the image can be processed, enhanced and communicated much faster than a conventional film. In fact, there exist three main ways of capturing a digital radiograph: the first is to scan a conventional film radiograph in a specialist scanner, similar to a document scanner. The second is to use a flat-panel similar to a digital camera, which converts the x-ray quanta directly in to charge. The flat panel is positioned in the same place as the film and is connected directly to a PC. CR uses a flexible imaging plate in the place of film. A chemical process in the imaging plate captures the radiograph. The imaging plate is then attached to a drum and placed in a scanner. This scanner reads the latent image off the plate. Exposing it to bright light erases the plate.

Film, Digital and Computed Radiographic Systems

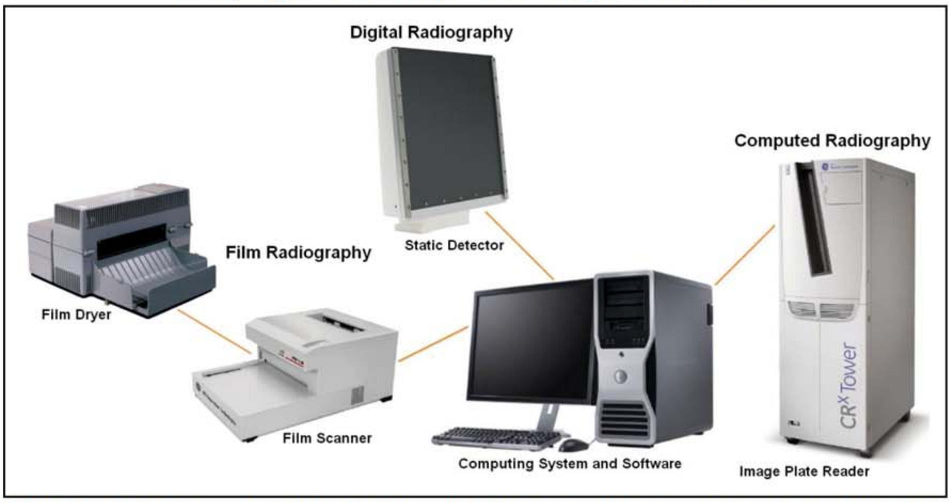


Figure 150 Different systems employed in film, digital and computed radiography methods in industry

Computed tomography, alternatively, uses a computer to produce 2D cross-sectionals and 3D images of a specimen from x-ray radiographs. Characteristics of the internal structure of a specimen such as dimensions, shape, internal defects, and density are readily available from CT images. The technique of tomography involves passing a series of x-rays through a specimen, and measuring the change in intensity or attenuation of these x-rays by placing a series of detectors on the opposite side of the object from the x-ray source. The measurements of x-ray attenuation are called projections and are collected at a variety of angles. Afterwards, each of these attenuation measurements are digitized and stored in a computer where a specialized algorithm is used to reconstruct the distribution of x-ray attenuation to produce a 2D cross-sectional image. X-ray attenuation corresponds to the grey levels in a CT slice, and reflects the proportion of x-rays scattered or absorbed as they pass through each volumetric pixel (i.e. a point in a regular space grid). If such process is repeated at various heights along the specimen, a series of 2D cross-sectional images is obtained, which can then be stacked on top of each other to achieve the 3D volume image.

An X-Ray Computed Tomography System

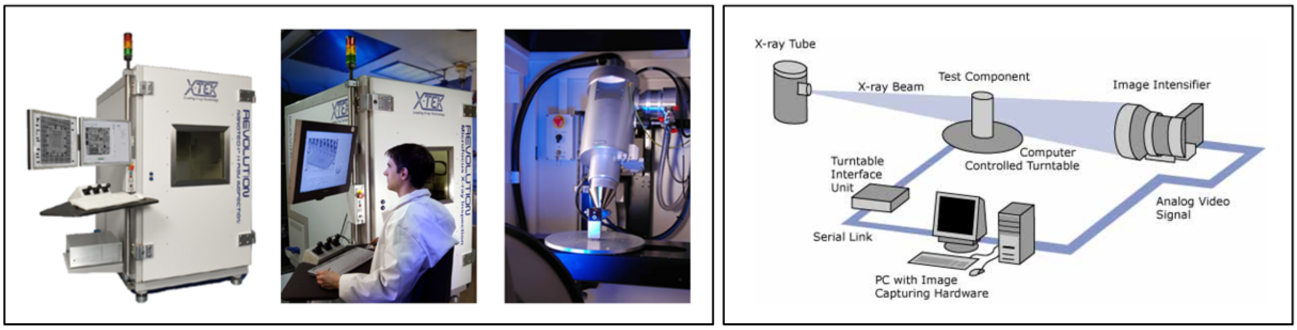


Figure 151 A micro-focus x-ray system with CT capabilities [WS112], and a schematic of such a CT system [WS67]

In neutron radiography, as neutron carry no electrical charge, they are non-ionizing and to generate a radiographic image on film, it is necessary to use a conversion screen that upon the neutron capture emits ionizing radiation or light that can expose film or be observed and recoded by a video recorder. There are different techniques that NR incorporates. The direct exposure technique endows with high resolution and excellent contrast and is usually referred to as the standard against which other techniques are judged. In this technique, photosensitive film and a gadolinium conversion screen are placed together in a light-tight cassette and exposed to the neutron beam. Track-etch technique is also a direct one that provides high resolution but low contrast and is insensitive to both gamma radiation and light. This technique employs cellulose nitrate film with a convertor screen that emits heavy charged particles. There exists an indirect exposure technique that is insensitive to gamma radiation and is usually used for inspection of highly radioactive components. It uses metal conversion screens (made from dysprosium and indium) that become temporarily radioactive when exposed to the neutron beam. Neutron radioscopy, on the other hand, utilizes a real-time technique using a scintillation or fluorescent convertor screen such as gadolinium oxysulfide to generate a light signal that is fed into a video system for viewing. Such a NS technique has relatively low spatial resolution and sensitive to gamma radiation but suitable for the inspection of parts and processes requiring instant feedback of information in manufacturing and processing plants [164], [502].

Image Reconstruction of a Diode Using NT

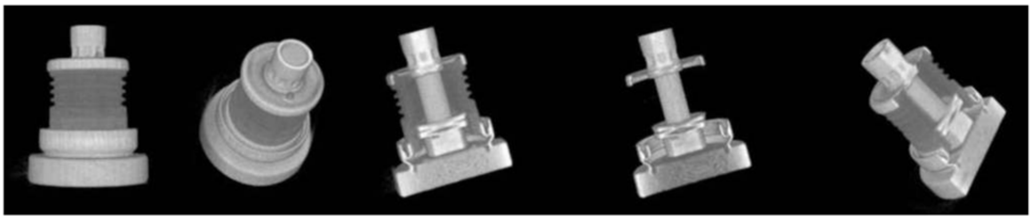


Figure 152 A multi-view image reconstruction of a diode using computer aided NT [336]

6.9.3 Use and Applicability

Radiographic testing is employed to detect the features of a machinery component or assembly that exhibit a difference in thickness or density as compared to surrounding material. Large differences are more easily detected than small ones. In general, radiography can detect only those features that have an appreciable thickness in a direction along the axis of the radiation beam. Therefore, the ability of radiography to detect planar discontinuities, such as cracks, depends on proper orientation of the test piece during inspection. Discontinuities which have measurable thickness in all directions, such as voids and inclusions, can be detected as long as they are not too small in relation to section thickness. On the whole, features that exhibit a 1% or more difference in radiation adsorption compared to the surrounding material can be detected [190].

RT is sensitive to cracks (provided that they are along the axis of the radiation beam), lack of fusion, lack of penetration, slag inclusions and porosity defects. However, minute discontinuities such as inclusions in wrought material, flakes, micro-porosity, and micro-fissures may not be detected unless they are sufficiently segregated to yield a detectable gross effect. Delaminations are not effectively identified by classic radiography due to their unfavorable orientation, which does not yield differences in adsorption that enable laminated areas to be distinguished from delaminated areas. The typical two-dimensional RT provides limited information about the depth of defect or the angular orientation of the crack. On the other hand, RT has proven to be extremely useful for inspection of groove welds in butt splices in plate applications [249]. The field inspection of thick sections can be a time consuming process as the effective radiation output of portable sources may require long exposure times of the film. This limits field usage to sources of lower activity that can be transported. The output of portable x-ray sources may also limit field inspection of thick sections, particularly if a portable x-ray tube is used. Portable x-ray tubes emit relatively low energy (e.g. 300 keV) radiation and are limited in the radiation output. Both of these characteristics of portable x-ray tubes combine to limit their application to the inspection of sections having the maximum adsorption equivalent of 75 mm of light metals. Portable linear accelerators and betatrons that provide high-energy (i.e. greater than 1 MeV) x-rays can be used for the radiographic field inspection of thicker sections [190].

Nevertheless, one of the effective field applications of x-ray RT is in inspection of multi-layer turbine blades which are said to be complicated objects for examination by nondestructive techniques (e.g. the blades of wind or gas turbine). These blades may have a number of layers with variable thickness plus an arbitrary curved surface. The blades are made from anisotropic materials and may also contain a lot of manufacturing non homogeneities [499]. As explained before, x-ray RT is based on the different levels of radiation absorption as passing through a material. Such RT systems are sensitive enough to detect change of at least 1-2% of the material thickness or density. In order to detect tight delaminations, having gaps less than 50 μm in width, the backscatter x-ray imaging technique can be used. The x-ray backscatter data contains quantitative information about variations in density, which is caused by changes in material properties or internal delaminations. Using this technique it is possible to locate the internal non-homogeneities within the depth of the material. The advantage of x-ray inspection is its extremely good contrast sensitivity; for instance, variations of density less than 0.1% are detectable in three dimensional perspectives [479].

Delamination and Lack of Glue in Main Spar of Wind Turbine Blades

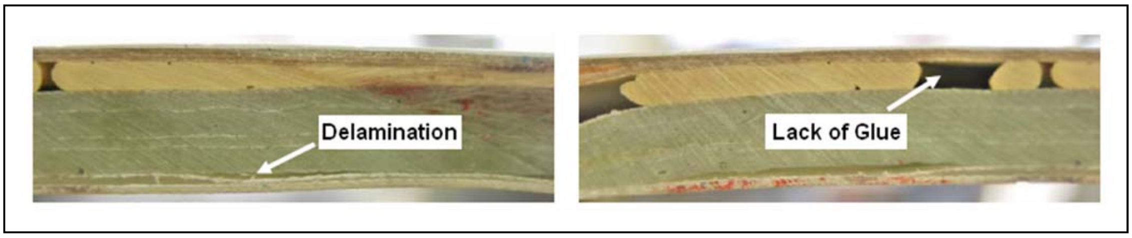


Figure 153 Cross-sectional view of main spar of wind turbine blades with delamination and lack of glue [499]

Another application of RT using x-rays and gamma-rays is measuring the wall thickness of insulated and uninsulated piping in service [172], [173], [259]. Besides, RT is capable of detecting internal corrosion, scaling and deposit in pipes [177], [185], [346], [685]. Furthermore, by combining imaging advancements and gamma-ray detector technology with robotics, it is possible to perform real time radiography and scan insulated or uninsulated piping for corrosion and erosion defects or loss of wall thickness. Such a system employs a linear array of solid state detectors on one side of the piping and a low intensity Ir-192 gamma-ray source on the opposite side. The detectors and source are mounted on a robotic crawler that travels at speed of 60 to 120 cm per minute and enable testing of pipes up to 75 cm in diameter [239], [646]. Radiographic imaging of piping components such as tees, elbows and valves is possible with more recent RT systems and technologies [238]. This is particularly essential as such components are subject to flow-accelerated corrosion and erosion.

RT Revealed Pipe Corrosion

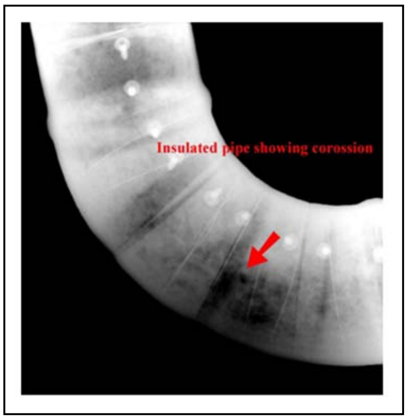


Figure 154 A picture captured by x-ray DR on site reveals corrosion in an insulated pipe [WS107]

As pipelines are the safest and most economical method for transporting fluids, they have been used for long time and consequently factors such as corrosion, fatigue and erosion amplify the risk of leaks or even bursts. For the inspection of pipeline two techniques are excellent due to their efficiency and ease of operation: ultrasonic and radiography. Since last decade there has been a large number of studies undertaken scrutinizing the accuracy and reliability of these techniques in detection of variety of weld defects; in addition, intensive researches have been run on automation of RT systems for pipeline and weld inspections [375], [376], [547], [649].

Da Silva et al. undertook a study to estimate the accuracy of RT technique in detection of weld defects developing nonlinear pattern classifiers, neural networks and different sets of digitalized RT films gathered from different sources [150]. The outcome was presenting high accuracy of classification for undercut, lack of fusion and porosity while for the other defects the results were not very satisfactory and particularly with slag inclusion showing the largest margin of confusion. Another research done by Carvalho et al. shows that, using artificial intelligence and neural networks, automated RT is not as capable as ultrasonics in detection of lack of fusion on the bevel wall of pipeline weld beads; however, coming to sizing the defects such as lack of penetration and undercut RT seems to be quite effective [112]. Indeed, using different RT methods, all the mentioned discontinuities and defects cannot only be found in pipes but in a wide range of machinery parts and structures [185].

Regardless of the machinery or equipment object and its shape (i.e. if it is flat or circular), RT can be used effectively to identify various weld defects such as undercut, lack of penetration, porosity, slag inclusion, crack and lack of diffusion, and material corrosion. Considering the radiographic film or screen of high-tech testing equipment, in welds, cracks are observed as dark, irregular but linear indications. Lack of fusion appears as a very narrow and dark line following a straight path (as opposed to a crack) along the contact region. Porosity, a gas hole in metal, is seen as a spot or field of spots darker than the surrounding materials. Inclusions of foreign matter are observed as either darker or lighter spots or fields, depending on the density of the foreign material relative to that of the weld material (i.e. lighter the density of inclusion, darker the color of indication). Lack of penetration can be visualized as very straight, dark, linear and usually crisp in sharpness. Besides, corrosion in different objects can be readily detected as the loss of material affects the exposure's characteristics. It is seen as a dark field with the thinnest areas appearing the darkest. Identification of corrosion by RT, for example, is quite beneficial in inspection of pumps [93], [264].

Radiographic Appearance of Some Weld Defects

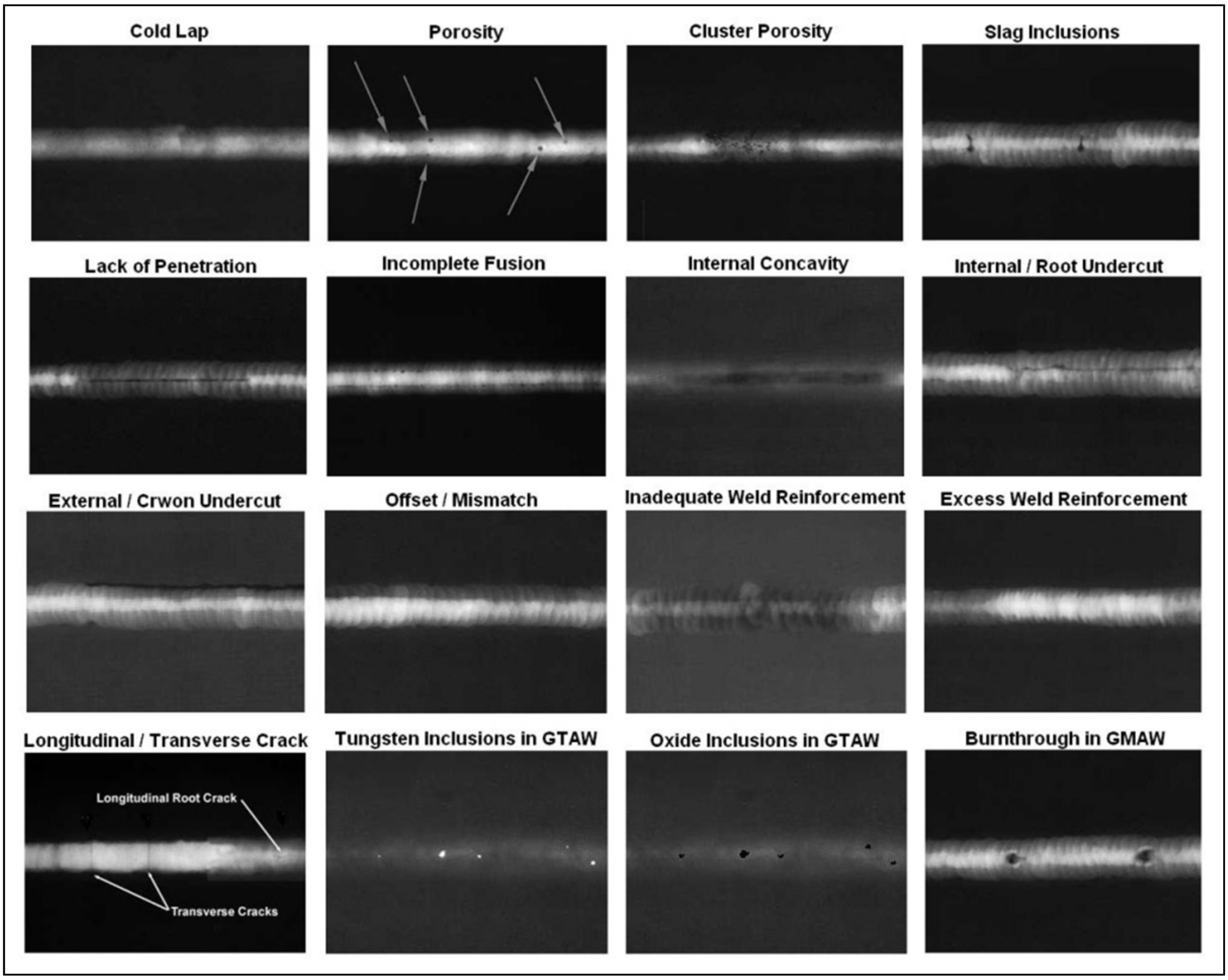


Figure 155 Some weld defects as they appear on radiographs [WS67]

Table 42 RT-detectable welding defects and their appearance [438]

Defect	Cause or Physical Appearance	Radiographic Appearance
Mismatch (SMAW)	Misalignment of pieces to be welded	Abrupt change in film density across weld width image
Offset weld (SMAW)	Misalignment and insufficient filling at bottom of weld	Abrupt density change across weld width; Straight dark line at center near density change
Burnthrough (SMAW)	A deep deprecation at the bottom of the weld	Localized darker density with fuzzy edges at the center of weld
Slag inclusions (SMAW)	Nonmetallic impurities solidified on weld surfaces	Irregular dark density spots
Cluster porosity (SMAW)	Rounded or elongated closely grouped voids	Darker density spots in randomly spaced clusters
Internal undercut (SMAW)	Gouging out of parent metal along bottom edge of weld	Irregular dark density streak near center of weld width
External undercut (SMAW)	Gouging out of top edge of piece to be welded	Irregular dark density along edge of weld image
Transverse crack (SMAW/GMAW/GTAW)	Weld metal fracture across the weld	Feathery twisting line of darker density running across weld image
Longitudinal crack (SMAW/GMAW/GTAW)	Longitudinal fracture of the weld metal	Feathery twisting line of darker density running length-wise along weld image
Internal concavity (SMAW/SMAW)	A depression in the center of the root pass	Elongated darker density area with fuzzy edges
External concavity (SMAW)	Insufficient filling	Weld density darker than the pieces across full width of weld
Interpass cold lap (GMAW)	Lack of fusion along top surface and edge of lower passes	Smaller spots of darker density, some with elongated tails
Scattered porosity (SMAW)	Rounded voids of random size and location	Rounded spots of darker density with random size and location
Lack of penetration (SMAW)	Bottom edges not welded together	Dark density band with very straight parallel edges at center of weld image
Tungsten inclusions (GTAW)	Random bits of tungsten fused into weld metal	Irregularly shaped light spots randomly located in weld image
Elongated slag lines (SMAW)	Solidified impurities on bottom surfaces	Elongated parallel dark density lines of varying width in longitudinal direction
Excessive penetration (SMAW)	Hot weld with extra metal at root of weld	High density in center of weld image; extended along weld or in isolated circular drops
Lack of side wall fusion (GMAW)	Elongated voids between weld beads	Elongated single or parallel dark density lines with dispersed darker density spots
Longitudinal root crack (SMAW)	Fracture in weld metal at edge of root pass	Feathery twisting line at edge of root pass
Root pass aligned porosity (GMAW)	Rounded or elongated voids in bottom center of welds	Round or elongated dark density spots in a straight line at bottom center of weld image

SMAW: Shielded Metal Arc Welding, GMAW: Gas Metal Arc Welding, GTAW: Gas Tungsten Arc Welding

Objects made of polymers and polymer matrix composites (PMCs) have relatively low density and hence do not absorb x-rays or gamma-rays efficiently. Although higher energy gamma and x-ray sources are not appropriate in this case, but low energy radiation (i.e. 10–40 keV) yields enhanced contrast for x-ray radiography of polymers and PMCs due to the nonlinear shape of the absorption versus energy curve [45]. Sala declares that the contrast can be enhanced by x-ray contrast agents or x-ray dye penetrants which consist of high density materials like chloroform (i.e. trichloromethane) liquid halogen compounds (e.g. methylene diiodide, diiodobutane, and diiodomethane) and are different from the dye penetrants used in visual penetrant testing [535]. Choice of the penetrant is determined by the ease with which it can penetrate the flaws and also with which it can be removed. Among those, Diiodomethane has the advantages of high opacity, ease of penetration, and ease of removal because it evaporates relatively quickly; however, it can cause skin burns. For this purpose, specimens are immersed in or the contrast agent is injected into the surface defects such as cracks and delaminations. Conversely, any pore, void, crack, or delamination not extending to the surface hence escapes detection. Additionally, sufficient wetting between contrast agent and material is important for complete penetration [405].

Besides, in radiographic testing of composites special electronic filters may improve detection of indications [405]. Some particular radiographic testing techniques such as x-ray compton back-scattering can yield indications of defects (i.e. including those that do not extend to the surface) such as delamination in PMCs without the use of contrast agents. Computer tomography has been started to get over of other RT methods in inspection of polymers and PMS; computer tomography has been increasingly used in research and development, and industrial use is incipient [229].

In addition to CT, neutron radiography finds various applications in the characterization of polymers and PMCs. Neutron scattering experiments investigate structure and behavior of polymers at the atomic level sustaining excellent accuracy of inspections for defects [306], [523]. Indeed, the dynamic range and speed of inspection are the driving factors in testing the composite materials.

The next application of RT and more specifically CR systems is in waxes and castings inspection. To illustrate, in foundries, an essential cost saving can be done by detecting defects in the wax part before the foundry process takes place. The reliability and the robustness of CR systems, makes this the ultimate solution in this application. The very short exposure time, and the fast scanning process, ensures high throughput and continuation of the production process, while digitalized images are almost immediately available after the exposure, and anywhere in the factory for making the most accurate decisions or corrective actions. In casting inspection the advantages of the high dynamic range plays its central role. Various thicknesses in difficult-to-penetrate materials needs bipack or tripack film systems, layering different sensitivities of film on top of each other, to cover the different thicknesses of the specimen [157].

Radiographic Appearance of Some Casting Defects

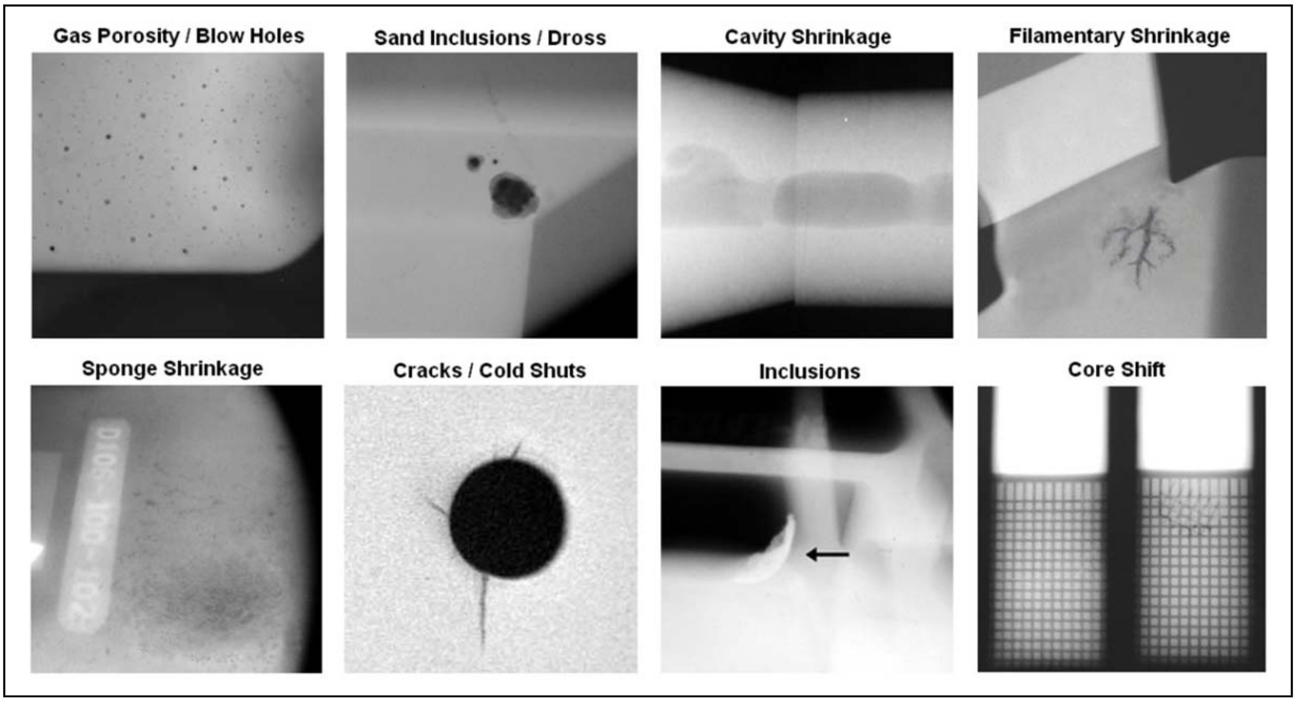


Figure 156 Some casting defects as they appear on radiographs [WS67]

Table 43 RT-detectable casting defects and their appearance [438]

Defect	Cause or Physical Appearance	Radiographic Appearance
Misrun	Failure to fill mold cavity	Appearance of large void-spaded indications
Hot tears	Restricted contraction prior to solidification	Dark ragged lines of variable width with numerous branches
Core shift	Mold movement during casting operation	Uneven internal wall thickness
Inclusions	Presence of sand, slag and other foreign objects	Irregular dark or light spots in castings depending on their relative density
Cold shuts	Imperfect fusion between two molten streams	Distinct dark line or band with smooth outline and variable length and width
Hot cracks	Fracture of metal in a hot plastic state	Parallel fissures
Gas porosity	Gas released during solidification or moisture	Smooth dark round or oval spots
Shrinkage cavities	Inadequate crucible feeding during casting	Moderately large irregularly void-shaped indications
Shrinkage porosity	Improper poring temperature or wrong alloy composition	Smooth dark round or oval spots

Recently, digital radiography has emerged as an outstanding inspection method for use in steam boiler applications. This is chiefly factual for those applications that entail corrosion fatigue cracking and weld quality [468], [645]. Indeed, DR provides an excellent scheme for the detection and evaluation of corrosion fatigue cracks in boiler waterwalls, riser tubes and associated link piping. Due to the exceptional dynamic range DR offers, it is possible to carry out many inspections without removing boiler lagging and insulation. Using the proper techniques and set-ups, it is also possible to trounce the thickness variations presented by buckstays, scallop bars and other external attachment obstacles. Besides, even very large pressure vessels and storage tanks can be inspected in relatively short time with use of portable RT imaging devices [149].

DR Application for Steam Boiler

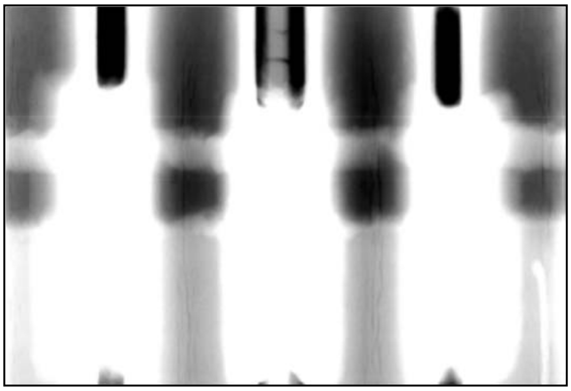


Figure 157 Corrosion fatigue cracking of waterwalls at lower wind box attachments of a steam boiler [WS27]

Neutron radiography is one of the most effective methods for radiography of radioactive specimens. Though, its applications are limited by the relative scarcity of suitable neutron sources and by the small cross-sectional areas of the available neutron beams. Nevertheless, taking into account the composite materials, Lovejoy declares that the x-ray attenuation coefficients of the different materials in bonded composite to metal joints or adhesively bonded honeycomb structure vary in such a manner that very little information regarding the bond can be attained by application of conventional x-ray techniques. NR techniques have been found to provide very clear pictures of both bond and composite in the presence of metals [386]. Hence, NR successfully facilitates examination of adhesive layers in composite materials, surface layers (e.g. polymers and varnishes). Currently, NR is one of the main NDT techniques able to satisfy the quality control requirements of explosive and flammable devices used in different industries. Besides, all types of o-rings and joints containing hydrogen can be inspected by NR even through a few centimeters thickness of steel. Dos Reis and, Bray and Stanley assert that NR is particularly useful in the detection of corrosion where there has been a minimum loss of material yet the corroded substance contains a high amount of hydrogen [164], [93]. Other applications of NR include: identifying coking and debris deposition in fuel nozzles; inspecting internal part alignment and presence (e.g. as o-rings upon valve assembly); imaging presence of casting voids in metallic structures; imaging presence of casting material and cracks in ceramics, metals and plastics; imaging structure of hydrogenous materials inside metallic structures that cannot be penetrated with x-rays; measuring hydrogen concentration profiles and diffusion in metals, measuring water diffusion in sealants, glues, and other waterproofing materials; and identifying corrosion in aluminum structures.

Neutron radioscopy, alternatively, has variety of applications in visualization of fluids flowing through metallic containers; indeed, hydrogen atoms included in such fluids are detected by neutrons. The main fields where NS has been used so far include: imaging fluid flow (e.g. water, oils, fuels, and lubricants) inside opaque objects (e.g. engines, transmissions, gearboxes, bearings and metallic structures in general); imaging injection molding of plastics and molten metals; imaging other hydrogenous and organic materials (e.g. oil seals, o-rings, and plastics) inside metallic and opaque structures (e.g. engines, valves, and transmissions); imaging fluid flow in porous materials (e.g. filters, and fluidized beds); visualization of two- and three-phase flow (e.g. air, water, particles) in heat exchangers, condensers and steam generator tubes; imaging the presence of cavitation in various types of fluid flow; imaging the advance of miscible and immiscible fluid fronts in porous media; imaging spray dynamics, structures, and behavior; imaging heat transfer dynamics associated with two-phase flow (e.g. boiling); and visualization of gas and liquid behavior in coolants and refrigerants.

As Richards et al. declare, since the initial development of NT method, it has been used very effectively to find low levels of hydrogen in metal matrices [514]. Further uses of the system have been to verify the exact placement, in three dimensions, of o-rings in large metal valve bodies and to map the location and extent of veins in porous and high-density materials of various kinds. NT has shown its capability to detect very small concentrations of hydrogen in titanium matrix [220], [417], [679]. Nevertheless, it is essential to underline that only materials with a certain range of attenuation coefficient are retained in the NT images. Besides, Vontobel et al. assert that NT can preferably be applied in cases where thick layers of (heavy) metals have to be transmitted and small amounts of light elements like hydrogen or boron have to be detected [642].

On the whole, radiographic testing is most satisfactory for identifying internal, nonplanar defects such as porosity and voids. Even with proper orientation and the forthcoming technologies, planar defects may be located. This nondestructive test is also apposite for detecting changes in material composition, thickness measurement, and locating unwanted or defective components concealed in the assembled machinery [93], [247].

Today, RT has a wide range of applications in industry which involve: product and assembly integrity inspection; pre-repair and post-repair machinery assessment; crack, material corrosion and erosion inspection (e.g. corrosion surveys on insulated and uninsulated pipes plus examination of valves for erosion); material loss and thickness measurement; information shots on industrial components (e.g. checking to see if a valve is closed properly, or checking for obstructions in valves and pipes); examination of boiler water walls; weld examination (i.e. for flaw detection and wall thinning); manual or automatic casting inspection (i.e. for cracks, hot tears, shrinkage, gas voids, porosity and cold shuts, misrun and unfused chaplets); high pressure braze joint inspection; and, wax pattern core integrity verification in casting foundries [157], [482], [578].

In fact, in manufacturing and production plants, digital or real-time radiographic systems can be designed and developed with automatic defect recognition (ADR) feature to seek, identify and alert for specifically known or suspected critical faults. This is an enormous labor-saving quality application of RT which can satisfy most needs as a quick method of inspecting components, locating and measuring defects and expressing 3D objects in two dimensions [166].

Some Applications of RT in Industry

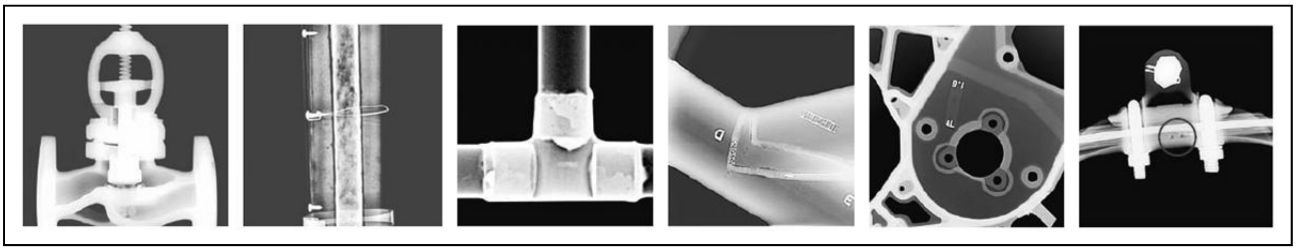


Figure 158 Several applications of radiographic testing in industry; from left to right: valve inspection, corrosion detection under insulation, cooper pipe brazing identification, weld inspection, casting inspection, examination of electrical cable clamp [WS107]

6.9.4 Limitations and Pros

Radiography is one of the most versatile NDT employed to identify a variety of defects. Film radiography is very sensitive technique for inspecting internal structure of a specimen. However, FR is a slow and rather expensive technique, especially in applications such as tube and pipe inspection where thousands of joints are to be inspected frequently. Digital radiography, on the other hand, is a suitable alternative to film radiography with considerable saving in running cost and processing time [296]. Different methods of radiographic testing are widely used throughout the industry. However, radiation used for radiography presents a potential hazard to radiographers as well as other personnel who may be exposed to radiation at the time of inspection. Due to its hazardous nature, the use of radiation is strictly controlled by regulatory authorities; in fact, this raises the testing costs associated with the advance training of radiographers and ultimate safety measures under request.

To more precisely express, film radiography offers several benefits: Among the existing radiographic methods, the cost of FR is relatively lower; the FR systems have the capability of rendering excellent image quality; plus, as the films or cassettes are portable, there is a great flexibility in positioning of the image receptor. However, FR has many drawbacks too. For instance, conventional FR relies on a combination of exposure factors and characteristics of the film and screen utilized to determine contrast and density levels. This range is limited and all pertinent information in the image may not be displayed. Once processed, the contrast and density levels present on the film are fixed. The user does not have the ability to adjust these values to display additional diagnostic information.

Moreover, radiographic film is subject to variables in processing conditions. Variations in temperature, chemical activity and transport time will result in inconsistent display of images. In addition, as the contrast and density on conventional FR systems are determined by wavelength (nm or Å) and radiation energy (keV) utilized; relatively minor variations in these factors may render the radiograph non-diagnostic. The resultant re-examination increases radiation exposure dose to the operator, increased material cost and inefficient use of technologist time. Another drawback is that since the FR film is bulky the cost of handling and distributing to areas where needed for diagnosis is high. Archived FR films require a significant amount of space for storage [186]. Additionally, conventional FR systems require the use of ID cards to imprint the specimen information on the film, file jackets to store and transport film files, clerical time to file specimen jackets and time to retrieve folders when prior images are needed for comparison to a current study. These administrative costs add to the overall total cost of operation for a FR system. Last but not least, FR film processing solutions contain chemicals that may be detrimental to the environment.

Table 44 Film problems in FR, causes and corrective actions [438]

Symptom	Cause	Corrective Action
Foggy Film	Exposure to light	Check for light leaks
Poor definition	Poor geometric exposure factors	Check all factors affecting shadows and unsharpness
Low film density	Underexposure	Increase exposure factors (check meters and timers)
	Underdevelopment	Check development time and solution temperature
High film density	Overexposure	Decrease exposure factors (check meters and timers)
	Overdevelopment	Check dark room timer and solution temperature
Low film contrast	Sample too thin, wrong film speed, underdevelopment	Reduce voltage, use high speed film, check developer intensity
High film contrast	Sample too thick	Increase voltage, use x-ray tube filter, or mask specimen
Spotted appearance	Fluorescent intensifying screen used	Try lead foil screen

The primary gain of digital radiography over film radiography is the opportunity to manipulate the specimen during radiographic inspection. This permits the inspection of internal mechanisms and enhances the detection of cracks and planar defects by allowing manipulation of the part to achieve the best orientation for flaw detection. Part manipulation during inspection also simplifies three dimensional dynamic imaging for the determination of flaw location and size. In FR, depth parallel to the radiation beam is not recorded. Consequently, the position of a flaw within the volume of a specimen cannot be determined precisely with a single radiograph. To determine flaw location and size more exactly with film radiography, other film techniques; such as triangulation, or simply making two or more film exposures with the radiation beam being directed at the specimen from a different angle for each exposure, must be used [190].

Coming to the computed radiography, the advantages are many. First of all, it is more environment-friendly as there is no silver based film or chemicals in use. Secondly, exposure times are a fraction of typical film exposures, which reduces occupational exposure to radiographers in field applications plus being more economical in addition to sustaining higher sensitivity [250]. Next is the speed of image acquisition which is much faster in comparison with the film radiography. Moreover, by adjusting image brightness and/or contrast, a wide range of thicknesses may be examined in one exposure, unlike conventional film based radiography, which may require a different exposure or multiple film speeds in one exposure to cover wide thickness range in a component. CR often requires fewer reshoots due to under- or over-exposure. Besides, CR images can be enhanced digitally to aid in interpretation and they can be stored on disk or transmitted for offsite review. Considering the costs, with chemicals, dark room storage and staff to organize them, one could own a CR for the same monthly cost of FR while being environmentally conscious.

On the other hand, CR has some drawbacks as well. It is still not an officially approved method for most higher quality radiologic applications (e.g. in aerospace), due to the possibility of digital manipulation to the captured image, the inherent geometric evenness and resultant lower spatial resolution as compared to film images, signal versus noise issues and sensitivity to scattered radiation, and the general lack of procedural consensus among primes and OEM's. In addition, the CR imaging plates are quite expensive and can be easily damaged, if the system being used requires manual handling of them. Besides, although theoretically the CR cassettes may be reused thousands of times, but in frequent use always result in damage, which eventually brings the necessary of replacement.

Computer tomography valuably grants quantitative information on the density and geometry of an object from 2D cross sectional images. CT holds many advantages over other RT methods as it completely eliminates the superimposition of images of structures outside the area of interest. Moreover, by CT differences between materials that vary in physical density by less than 1% can be distinguished due to its inherent high-contrast resolution allowing CT to be able to highlight structural irregularities. In addition, as CT images are digital, they may be enhanced, analyzed, compressed, archived, and be used in performance calculations which enables comparisons with other NDTs.

CT has limitations as well. Firstly, objects under inspection must be small enough to be accommodated by the CT equipment and can be fully penetrated by the x-ray energies used by that particular system. Secondly, CT reconstruction algorithms require gathering of a full 180 degrees of data by the scanner. Last is the possibility of relics in the data, which limit a user's ability to quantitatively extract density, dimensional, or other data from an image. Hence, the user must gain knowledge of and be able to recognize and disregard common relics and artifacts (e.g. pressure marks and dirt).

Overall, CT is an ideal choice whenever the primary goal is to locate and size planar and volumetric detail in three dimensions. CT permits the physical characterization of the internal structure of materials due the good penetrability of x-rays. Besides, since it is x-ray based, it can be used equally well for metallic and nonmetallic objects, solid and fibrous materials, and smooth and irregular surfaced specimens. Furthermore, the exceptional ability of a CT system to image thin cross sectional areas of interest through a specimen signifies the fact that CT data can provide evaluations of material integrity which cannot currently be provided by any other NDT method.

Neutron radiography has the unique ability to image certain elements and isotopes that are either completely undetectable or poorly detected not only by other RT methods but also by other NDT techniques. However, there are some materials as well which cannot be clearly imaged via NT. For instance, organic materials or water are clearly visible in neutron radiographs because of their high hydrogen content, while many structural materials such as aluminum or steel are nearly transparent. Other neutron radiographic methods such as NR and NT have many advantages and disadvantages which are already mentioned throughout this chapter. Though, on the whole, the major disadvantage of neutron radioscopy is poor image resolution while the advantages include good image contrast, reduced exposure time, very good image linearity and the ability to manipulate image data [372]. A drawback of neutron tomography is the time it takes to collect a complete data set. For example, during the image acquisition the object must remain in the same state or else there will be blurring in the reconstructed image. While this is no problem for static objects, it can be a major challenge for moving objects in operation.

In general, radiographic testing methods have the following advantages: they are applicable to almost all materials; they generate permanent records that are readily retrievable for future reference; they are capable of identifying surface, subsurface and internal discontinuities; they can disclose fabrication errors at different stages of manufacturing; and, there exist wide variety of portable equipment in the market. The overall disadvantages of radiographic testing methods are: they are relatively expensive (incl. cost of equipment and the accessories related to radiation safety); radiation used is hazardous to the personnel; they are not effectively capable of detecting laminar discontinuities; some RT equipment are very bulky; RT requires two side accessibility for inspection of any object; testing results are not fully instantaneous (i.e. it requires image processing and interpretation); RT requires highly trained personnel in the subject of radiography as well as radiation safety; and, the companies applying RT need to be licensed and subjected to various rules and regulations.

Eventually, it is essential to note that radiographic quality or sensitivity is a function of graininess, resolution and contrast. Graininess is associated with the film development process and depends on both film type and processing. Coming to resolution, related unsharpness is the cumulative effect of movement unsharpness, detector unsharpness and geometric unsharpness. The first is an outcome of movement of film, object or radiation source. The second is dependent on the detector materials and their light-scattering-related features. The third is caused by the finite size of the radiation source, and the relative distance of the source, object and film or detector. Contrast, on the other hand, depends on the test object (e.g. its thickness and density), film or detector characteristics (e.g. film type, speed, density and the processing procedure), and the penetration characteristics of the source [264]. In fact, a radiographer has to be well trained to be able to attain the best image quality and greatest radiographic sensitivity by means of the available equipment.

Having a comparison among different NDTs, radiography and ultrasonic are the two generally-used methods that can satisfactorily detect flaws which are completely internal and located well below the surface of the object. Neither method is limited to the detection of specific types of internal flaws. However, radiography is more effective when the flaws are not planar, while ultrasonic is more effective when flaws are planar. In comparison to other generally-used NDT methods (e.g., magnetic particle, liquid penetrant, and eddy current testing), RT has advantageously the ability to inspect for both internal and external flaws, covered or hidden parts or structures and significant variations in composition. Plus, it provides a permanent recording of raw inspection data. Nonetheless, it is essential to underline that industrial radiography (i.e. RT in manufacturing, processing and power plants) appears to have one of the disfavored safety profiles of the radiation professions. The case is more evident specially when there are operators using strong gamma sources in remote sites with little supervision when compared with radiographers within the nuclear industry or hospitals.

Table 45 Synopsis of radiographic testing

Pros	▪ Minimum part preparation ▪ Inspection of hidden areas ▪ Applicable to almost all materials ▪ Good definition of the discontinuities ▪ Some portable equipment are available ▪ Chance of controlling of inaccessible zone ▪ Ability to locate surface and internal defects ▪ Accurate and permanent test record obtained ▪ Detection of surface, subsurface and internal discontinuities ▪ As a versatile test, can be used for inspection of many shapes and sizes	
Limitations	▪ Mobility ▪ Expensive ▪ Safety hazard ▪ Requires two side accessibility ▪ Some equipment are very bulky ▪ Relatively slow rate of inspection ▪ Strictly regulated by governments ▪ Results are not fully instantaneous ▪ Depth of discontinuity cannot usually be identified ▪ Laminar discontinuities cannot usually be detected ▪ Very sensitive to flaw orientation (highly directional) ▪ Decrease of detection effectiveness with increasing thickness ▪ High skill and training required for implementation and interpretation, and safety concerns	
Equipment	▪ FR requires film processing and development facilities and equipment ▪ Portable or fixed units depending on industry requirements and testing purposes	
Discontinuity types	▪ Void ▪ Burst ▪ Crack ▪ Porosity ▪ Hot tear ▪ Cupping ▪ Cold shut ▪ Corrosion ▪ Shrinkage	▪ Lamination ▪ Weld defect ▪ Slag inclusion ▪ Lack of fusion ▪ Micro-shrinkage ▪ Water entrapment ▪ Lack of penetration ▪ Material's non-uniformity ▪ Material's density change
Discontinuities size	▪ Most recent RT systems can identify flaws as small as 25 microns ▪ Discontinuities that shows as low as 1% absorption variation relative to contiguous area	
Relative inspection cost	▪ Very expensive in terms of both man power and required equipment, but costs can be reduced with the use of portable equipment	

6.10 Stress Wave Analysis

Stress wave analysis (SA), also abbreviated as SWAN, is one of the condition monitoring techniques to measure friction, shock, and dynamic load transfer between moving parts in different machinery particularly in rotating and reciprocating mechanisms. The analysis process consists of real-time measuring and assessing data which is in fact coupled with sounds passing through a machinery structure at ultrasonic frequencies due to friction and shock incidents between its moving components. This high frequency acoustic sensing technique facilitates the maintenance experts with filtering out background levels of vibration and audible noise, and illustrating current machinery condition in a graphical manner. SA identifies wear and damage at the earliest stages by quantifying the stress wave energies of shock and friction events, tracking the progression of a defect throughout the failure process via its increasing stress wave energy content, and comparing these values to ones associated with the normal machinery conditions [97].

6.10.1 Conception

Scientifically, stress wave is particular type of acoustic emission. Acoustic emission is described as the class of phenomena whereby quick release of energy from a localized source within a material forms transient elastic waves. Stress waves are a subclass of such phenomena whereby elastic waves are incessantly produced subsequent to the contact stresses between two surfaces with relative motion. In fact, stress waves can be distinguished with their higher energy content in comparison with other types of acoustic emissions. It is because of this higher energy content that stress waves are able to propagate profoundly through solid structures and across material interfaces, such as bolted flanges, mating gear teeth, and antifriction bearing rolling elements; thus, they can be relatively easier identified and measured [276], [651].

The SA condition monitoring technique employs special instrumentation to measure and quantify friction, shock, and dynamic load transfer between moving parts in different machinery. SA is an electronic means of detecting and analyzing ultrasonic sounds that travel through a machinery structure. The SA systems incorporate exclusive transducers that utilize their resonant frequency to selectively amplify low amplitude stress waves, and specialized signal conditioning to filter out structural vibration. As the high frequency stress waves propagate into the transducer, a piezoelectric crystal resonates at 40 kHz, and converts the stress wave amplitude into an electrical signal, which is then amplified, band pass filtered and demodulated, to remove unwanted low frequency sound and vibration energy. The output of the signal conditioner is a pulse train that presents a time history of individual shock and friction incidents in a machine. There is a digital processor which analyzes the pulse train to compute the peak amplitude and the total energy content generated by each friction or shock incident. The computed peak amplitude and energy content values are recorded in a database for comparison with and historical trending against the normal readings. The level and pattern of irregular or inconsistent shock and friction incidents can be effectively used as a diagnostic tool [86].

Stress Wave Analysis

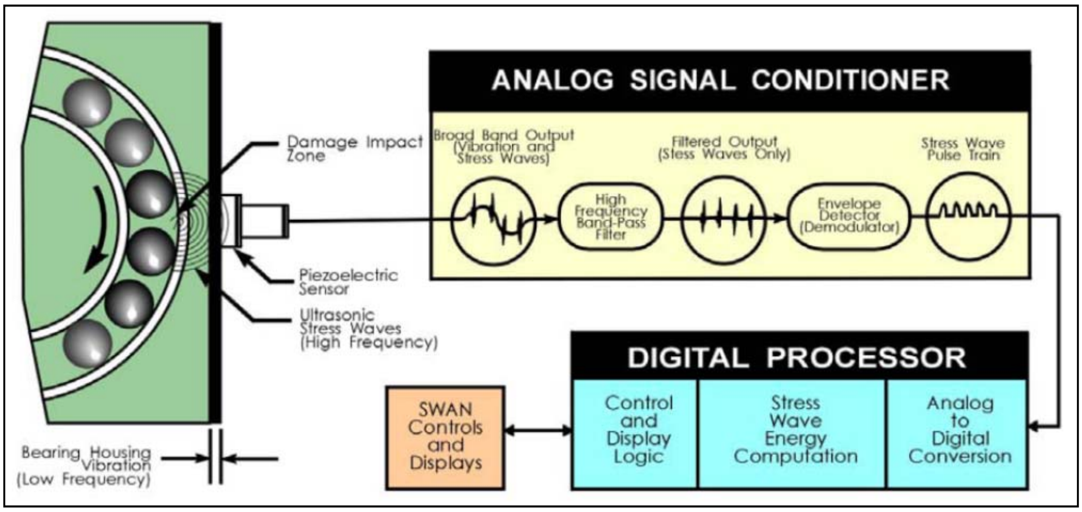


Figure 159 A picture illustrating the fundamental processes that are incorporated in stress wave analysis [86]

As mentioned, stress wave analysis involves computing both the amplitude and the energy content of detected stress waves. The amplitude of a stress wave is a function of the intensity of a single friction or shock incident. The energy content is a computed value that considers the amplitude, shape, duration and rates of all friction and shock incidents which occur during a time interval. Figure 160 shows the stress wave energy variation for a bearing with spall, for which the peak level of detected stress waves is a function of the spall depth, while the stress wave energy is a function of spall size and depth [87].

Stress Wave Energy

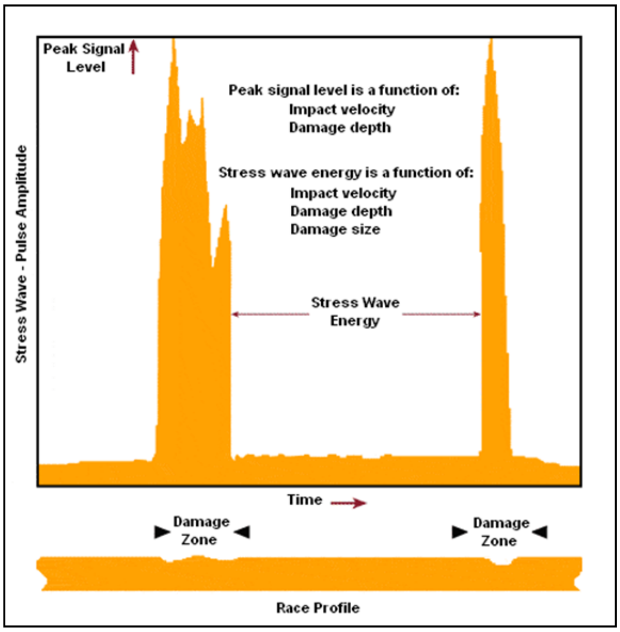


Figure 160 Stress wave energy variation of a spalled bearing [87]

6.10.2 Tools and Techniques

When machinery components come in contact with defective parts, even at the earliest stages, shock and friction incidents generate stress wave energy. Stress wave analysis detects and measures this energy at damage levels well below the degradation required to excite vibration sensors, and before sufficient damage has occurred to make metal chip detectors triggered in lubrication systems. Such a sophisticated performance is achieved via examining the data collected by very hi-tech stress wave sensors which have been developed for the purpose of identifying the current operating condition of machinery. Stress wave data is collected by a data collection unit which is located next to the machinery being monitored. Depending on the mechanical complexity of a given machine, multiple sensors (i.e. two to eight sensors) may be needed to effectively exemplify the machinery condition. The data collection unit periodically takes high-speed data samples from each of the connected sensors and converts and derives from these data sets, which are called digital records, several statistically analyzable factors as followings [509], [549]:

- Stress wave energy history chart, which illustrates a trend of stress wave energy readings over time, and presents them against the back drop of the green, yellow and red health indicating color zones. This is in fact an easy-to-interpret graphical representation of the health trend of the machine that exhibits damage levels based on a failure progression curve. The stress wave energy history charts can be employed to detect and quantify a wide range of damage levels in gear and bearing systems. They can also present lubrication quality problems and contamination, and abnormal preloads due to misalignment or improper machinery assembly after overhaul or repair. For a stress wave energy history chart, the energy values can be used to calculate caution and warning limits, which are the baselines of yellow and red zones respectively. The caution limit is computed as the mean plus three times the standard deviation of stress wave energy readings obtained over 10 to 60 minutes of steady state operation. The warning limit is determined as ten times the mean stress wave energy value during the same period of time. These limits are conservative because friction energy losses in healthy machines are very stable and increase by more than a factor of 10 early in the failure process for most catastrophic failure modes.

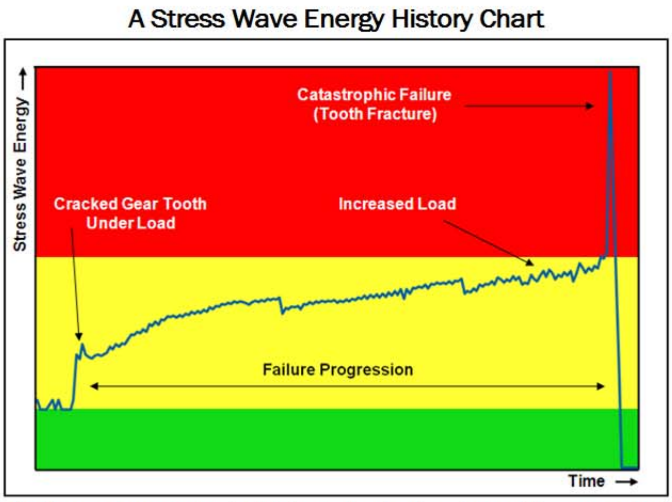


Figure 161 A stress wave energy history chart of a gear with a cracked tooth [98]

- Stress wave amplitude histogram, which shows the peak amplitude of each pulse in the stress wave pulse train and indicates if the stress wave distribution is normal (i.e. bell shaped) and at the lower end of the amplitude scale. To illustrate, for a healthy machine as the friction incidents are consistent and at low levels, the distribution is a narrow bell shape and at the lower end of the voltage scale. In an abnormal machinery condition, which is, for example, a result of lubrication problems such as fluid or particulate contamination or skidding between rolling elements, increasing number of higher amplitude friction and shock incidents happen. The histogram shows a much broader distribution that is skewed to the right on the amplitude scale. The stress wave amplitude histogram can be practically used to detect irregular incidents which are linked with lubrication problems such as fluid or particulate contamination or skidding between bearing rolling elements and races.

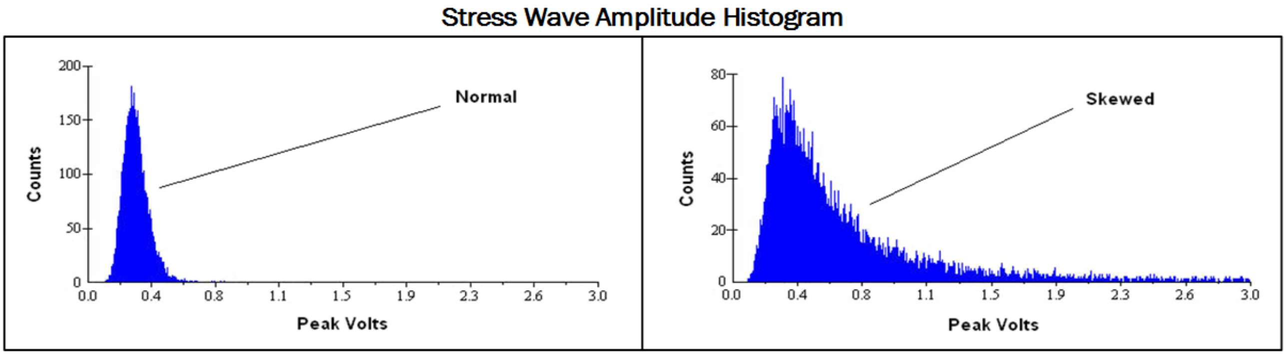


Figure 162 Stress wave amplitude histograms of a healthy machine on the left and a machine with detrimental condition on the right [86]

- Stress wave spectrum, which shows stress wave pulse amplitudes as a function of the repetitive frequencies at which they occur. Indeed, the transducers used for stress wave analysis only detect incidents that excite them at 40 kHz so that the vibration signals associated with machine dynamics are filtered out, and a time history of only shock or friction modulating incidents is recorded. For a machine in normal condition, a minimal number of shock incidents happen; therefore, the spectrum demonstrates relatively flat horizontal line with no significant spectral lines. In case of presence of a localized damage like a spall on the race of a rolling element bearing or on a tooth of a gear, a repetitive shock incident occurs as the damaged zone gets in contact with neighboring parts. In the stress wave spectrum, such repetitive shock incidents appear as a spectral line more than 10 db above background levels and at the frequency that they occur. In this case, the rotating speed and geometry of the machinery components like gear and bearing elements can be assessed to precisely identify the component and the damaged zone that cause shock at that specific frequency. The stress wave spectrum is very sensitive to abnormal dynamic loading and to very small levels of localized fatigue damage at early stages.

Stress Wave Spectrum

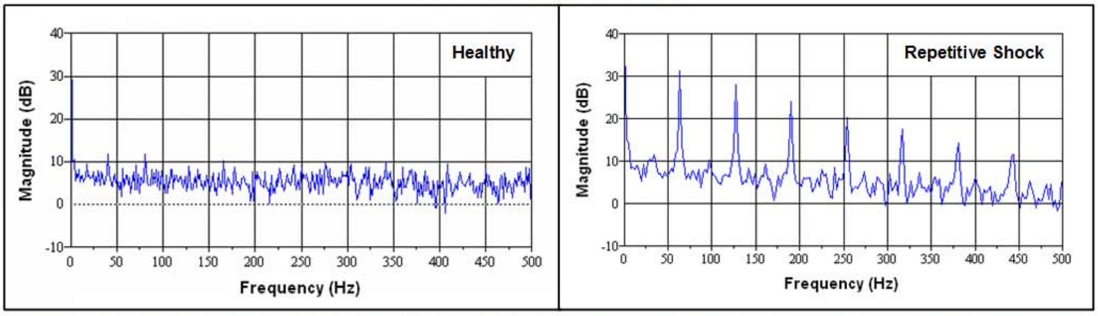


Figure 163 Stress wave spectrums of a healthy machine on the left and a machine with detrimental condition on the right [86]

SWANtech, based in Virginia, U.S.A., is the major company which develops and produces stress wave analysis systems in the world. Their stress wave analysis systems are consisted different components and software. Externally mounted, highly sensitive sensors on a machine's housing detect stress waves transmitted through the machine and convert the data into electrical signals, which are then filtered, measured and analyzed for energy content by an on-board microprocessor built in a real time monitoring unit called SWANguard. A SWANguard can support one to eight sensors and monitor one or more assets, depending on the equipment complexity. For simple machines, a single sensor may be sufficient. SWANguard, connected to sensor and power, reads stress wave energy values and divert them to analog signals. These diverted values along with computed amplitude and total accumulated energy are then routed to the site server (SWANserver) for further data analysis through an Ethernet or a wireless system.

Stress Wave Analysis Equipment

Figure 164 Some stress wave analysis equipment such as sensors, wired and wireless signal monitoring and processing units [WS92]

SWANserver is a computer module that collects the stress wave data from every SWANguard in a facility on a constant basis, and creates operating condition indications for every monitored machine. Depending on the plant layout and facilities, the communications between the site server and the SWANguards can be a combination of wireless, serial cable, Ethernet and fiber-optic connections. In addition, the site server interfaces with the plant automation and control systems to record the key plant operational parameters under which the machinery work. The site server automatically correlates the stress wave energy readings with machine loading or other operational parameters such as RPM and head pressure to learn what levels of energy are normal for each machine, at their various levels of exertion. This allows the server to identify anomalous energy levels that may represent increased wear, mechanical degradation or possible lubrication problems. The data collected by the site server provides operating history and the feed to be used by different analytical software to compute the condition index values and particular statistics for each machine. E-mail notifications and work order initiations can be automatically sent in case of abnormal machinery conditions.

Typical Configuration of a SA System in a Plant

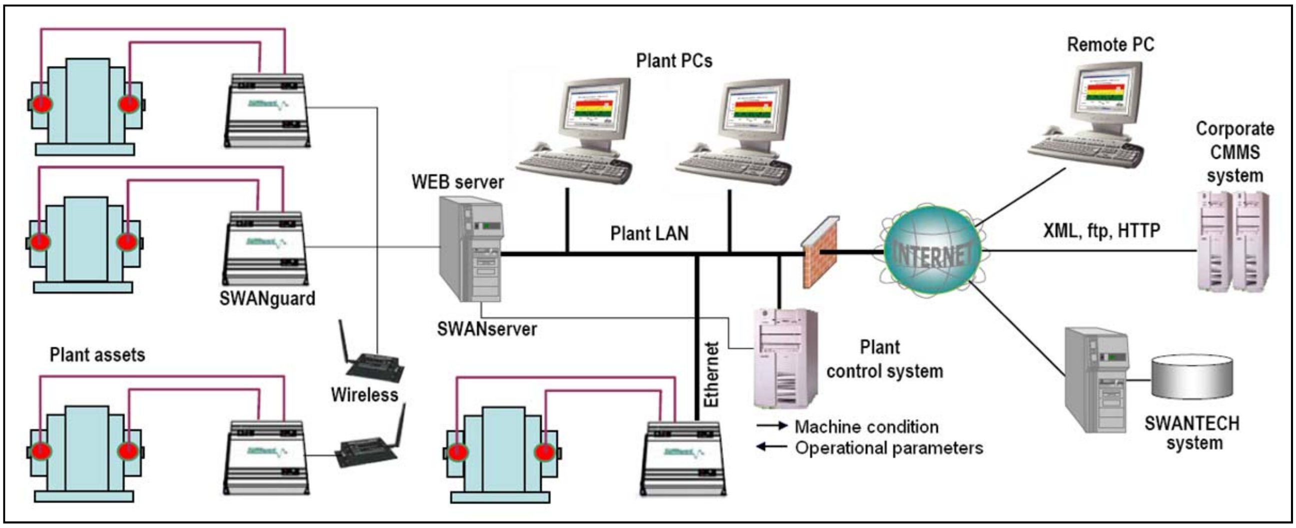


Figure 165 A typical configuration of a stress wave analysis system in an industrial plant [WS92]

6.10.3 Use and Applicability

At the beginning, stress wave analysis was developed to determine abnormal sources and causes of friction and shock such as damaged gears and bearings in complex gearboxes, for which vibration analysis had been proved to be ineffective. Later, SA has been effectively employed to diagnose the condition of gears and bearings in numerous types of mechanical drive trains. Nevertheless, it is also useful in identifying the lubrication quality and abnormal loads due to misalignment or improper machinery assembly. Additionally, localized fatigue damage on rotating components of a wide range of machinery can be determined via stress wave analysis. Nowadays, SA is a useful condition monitoring technique on a wide array of rotating machinery including gearboxes, motors, pumps and turbines and also for slow speed, partial cycle, and reciprocating machinery, condition of which has been formerly difficult to be monitored and assessed [86], [87].

In fact, stress wave energy is directly proportional to the friction between moving parts that are separated by a lubricant boundary layer. Since friction is a function of both speed and load, SA is an exceptionally useful for understanding dynamic loading and lubrication condition in operating machinery, as well as detecting classic rolling element defects and imbalances. In this respect, friction is said to be a first order response to changes in load, speed and component health, whereas temperature and vibration tend to be second order responses. Friction is an immediate response, and will change by orders of magnitude in proportion to input forces and component health. This makes stress wave analysis an effective early warning system, because it can distinguish between mechanical component health and operating condition.

A Stress Wave Energy Sensor

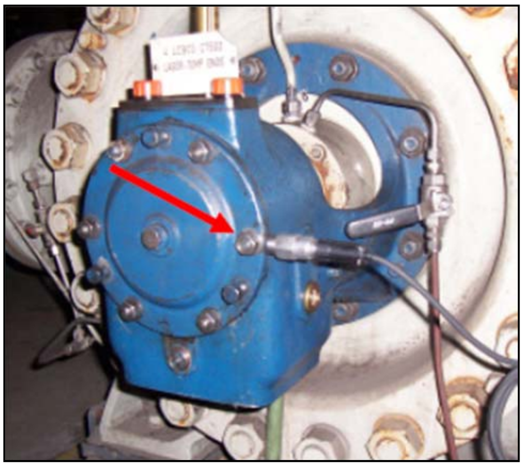


Figure 166 A picture showing the location of a SWAN sensor on a pump’s bearing housing [98]

One of the applications of stress wave analysis is in condition monitoring of low speed rotating machines have been utilized broadly in different industries. There is no universally accepted criterion based on which machines are categorized as of a low speed class. However, it is generally accepted that 600 rpm is the minimum speed for the intermediate speed category and any below speed can be considered as a low speed. Traditionally, vibration analysis has been effectively used to identify loss of mechanical integrity of a wide range of rotating machinery. Still, machinery rotating at low speed is difficult to be diagnosed as, in this particular case, vibration analysis is not capable of measuring the fundamental frequency of operation, and the distressed rotating component at low speeds does not necessarily indicate a clear change in vibration signature.

The major problem with the condition monitoring of low speed machinery has two aspects: feature extraction and pattern classification. The first is more essential as the effectiveness of the pattern classification is dependent on it. Many low speed rotating machines are usually heavy loaded and their defect frequencies are so low that most valuable defect information is plunged in the background noise. To overcome the intrinsic low frequency instrument noise problem, many transducers and analyzers are fitted with high-pass roll-off filters at around 5 Hz. Though, the once-per-revolution features associated with many defect conditions are remained undetected within the 0-5 Hz frequency range. Besides, multi-defects may concurrently occur in the mechanical systems [414].

Hence, there is a need to separate the different sources when the mixing paths of vibration and source signals are neither controllable nor known. Stress wave analysis combined with supremacy of neural networks can be effectively used to chuck out the noise contained in the vibration signals and extract the essential multi-defect features [282]. High-frequency stress wave analysis can be employed to detect the early stages of the loss of mechanical integrity in low speed machinery, in which the sources of stress wave is the relative movement between mating components experiencing loss of mechanical integrity such as loss of tightening torque between clamped parts [300], [415].

Since early 1970s there have been many empirical researches about stress wave emission during fracture in various structures from bars to plates and in different materials from steel to polymers [243], [480], [508], [607], [620]. In recent years, the research has been also focused on multi-layer composite materials which have been increasingly used for many structural applications [62], [602], [604]. In the work of Tasdemirci and Hall the stress wave behavior of a multi-layer material consisting of ceramic, copper and aluminum subjected to large strains under high strain rate loading was investigated through a combination of experimental and numerical techniques [603]. They found that the presence of a ceramic layer increases the magnitudes of stress gradients at the interfaces. In fact, severe stress irregularities that may exist in multi-layer composite materials make their condition monitoring via stress wave analysis complicated.

SA can also be used to monitor the integrity of cracked components prior to their fracture. Maekawa claims that the impact fracture strengths of such components are impinged on the loading direction and the length of the components subjected to an impact force [395]. His research exhibits that the impact tensile fatigue life and the fracture strength of a short component is less than that of a long one. In fact, the engineering materials typically contain holes, cracks and obstacles, and usually present inhomogeneous mechanical properties. Under impact loadings, the high frequency modes give rise to the responses of these materials as complex stress wave propagation, reflection and diffraction on the inner or outer boundaries, corners and crack tips. The anisotropy (i.e. having different properties in different directions) of materials alter the stress wave propagation, and the defects and obstacles act as refractors, scatters and concentrators of stress waves, both of which will largely determine the distributions and orientations of energy propagation and the forms of dynamic failure [211]. It is with the clarification of the mechanism of the interaction between transient stress wave propagation and obstacles or defects that the condition of a machinery component can be identified.

Another application of SA is in monitoring of dynamic buckling of cylinder and tube like mechanical structures. Twin walled cylinders are used widely as energy absorbing devices as they are not expensive, efficient and reliable. Dynamic elastic-plastic buckling of such structures is a complex phenomenon that is sensitive to inertia and strain rate effects [254], [596]. The elastic-plastic stress waves resulting from axial impact of cylinders with different wall thickness can be studies and analyzed to quantitatively determine the severity of the buckling and the condition of the object [312].

In the same manner, SA can be utilized for condition monitoring of variety of tubes subjected to axial impact loadings. This is useful for square-shaped tubes which present a large variety of buckling patterns. In such tubes, the initiation of buckling starts far from the shell ends for both low and high velocity impacts. Plus, their dynamic plastic buckling occurs at much lower impact velocities and for materials with much lower strain hardening properties in comparison with circular tubes having the same thickness or solidity ratio [313].

6.10.4 Limitations and Pros

SA enables identifying very slight shock and friction incidents that occur between contacting surfaces. It also provides the capability to localize a fault to a particular gear or bearing, and even to an individual race or rotating element within a bearing. Hence, it has a very high sensitivity degree in comparison with other similar condition monitoring techniques. SA is able to determine the probability of failure, identify the damaged components accurately, and provide the time required to fix the problems at early stages prior to the occurrence of secondary damages or catastrophic machinery failures. Another advantage is its ability to differentiate stress waves from the much lower frequency range of operating machinery vibration and audible noise. This is indispensable for monitoring machinery in operation for damaged gears and bearings as during early stages of damage the energy released from their contact surfaces is usually too minute to agitate gearbox or engine structures to the levels noticeably above background vibration levels until far-reaching secondary or catastrophic failure damage take place [549].

Besides, it is essential to underline that SA is technically based on the direct measurement of friction and impact incidents occurring inside of the machine under monitor. In contrast with many condition monitoring techniques that require identifying the baseline operational traits of a machine to determine its normal condition, SA technique does not need such a process as it identifies a problem without reference to prior experience on the same or a similar machine. It is clear that there should not be any properly manufactured and maintained machine with high friction levels between its moving parts. Even a grinding or milling machine is not expected to have high friction levels in its drive train. Of course, there are some machines like reciprocating compressors that demonstrate periodic impact incidents in their normal operation but even those types of machinery should not exhibit new impact incidents over time. Therefore, with use of the SA technique the normal condition of any machine can be promptly verified; and subsequently, any deviations can be identified and tracked.

Different Symptoms in Failure Progression of a Gear

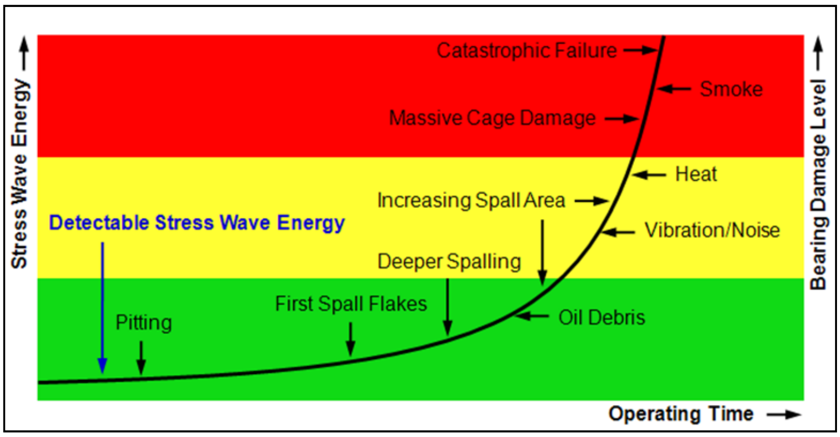


Figure 167 Various defect indications of a gear’s progressing failure over time [86]

Another merit is that it needs almost no operator training, even an inexperienced operator can identify potential problems well before they divert to failures. SA facilitates considerably simplified data interpretation and can gauge trends in failure progression. In most of the cases, the SA systems grant fault detection superior to vibration analysis, particularly in the earliest stages of failure progression. Such a prior detection in time may avert potential catastrophic consequences that could develop due to failure of a critical pump, motor, generator or other machinery. Moreover, the exact location of a potential damage can be identified among a machine’s individual components, thereby enabling operators to efficiently conduct predictive maintenance in advance of failures. The technology also provides trends of damage progression which are essential for maintenance of different machinery.

Comparative Cost-Time-Application of Different Condition Monitoring Techniques

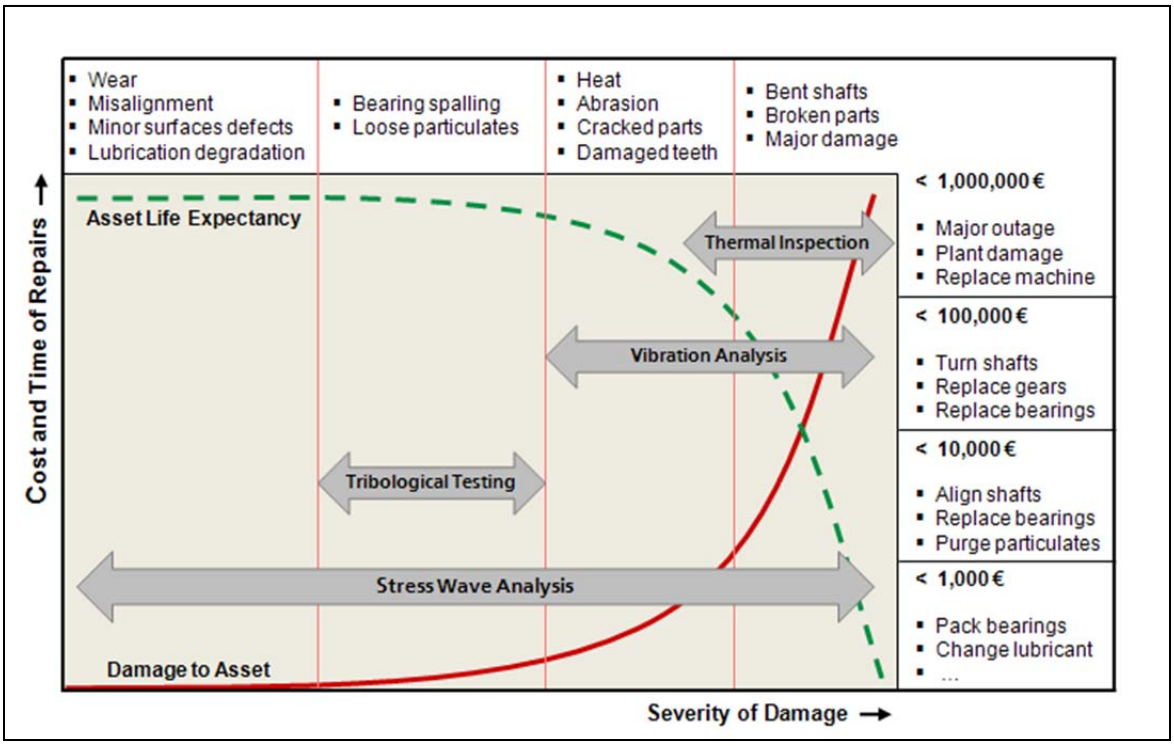


Figure 168 A comparative overview of cost, time and application stress wave analysis [98]

On the whole, stress wave analysis is an online condition monitoring technique which does not require expert knowledge to be carried out as the test results are easily interpretable without special training [509]. It is also capable to provide some information about the cause of components wear. In addition, it provides the ability to identify leakages in gas and liquid stuffed systems under high pressure. It is also useful in determining the quality and effectiveness of lubricants. In comparison to vibration analysis, the SA online system has no monitoring lack and do not need measurements by hand. Moreover, the stress wave analysis needs just a third of the sensors that are used for the vibration analysis. And as mentioned before, the measurements can be evaluated by any staff without special training in opposition to the vibration analysis for which an expert usually is required.

Table 46 Synopsis of stress wave analysis

Pros	▪ Immediate results ▪ Minimum skill required ▪ Relatively easy to perform ▪ Early problem identification ▪ No part preparation required ▪ Low incidence of false alarms ▪ Trends of damage progression ▪ Sensitive to small discontinuities ▪ Fast, reliable and accurate output ▪ No analysis of kinematics required ▪ An online condition monitoring technique ▪ Accurate and permanent test record obtained ▪ Possibility of measurements in areas inaccessible or hazardous	
Limitations	▪ Mobility ▪ Incapable of determining the depth of discontinuity ▪ Equipment and instruments are relatively expensive	
Equipment	▪ Required stationary devices include sensors, processing units, a data server and personal computers.	
Discontinuity types	▪ Crack ▪ Pitting ▪ Fatigue ▪ Spalling ▪ Disbond ▪ Abrasion	▪ Corrosion ▪ Impact wear ▪ Delamination ▪ Impact damage ▪ Surface-breaking
Discontinuities size	▪ Very small to very large discontinuities can be found	
Relative inspection cost	▪ Equipment costs are comparatively high but the total initial investment depends on the scale of plant and number of machinery to be monitored. Man power costs, excluding primary trainings, are supposed to be low.	

6.11 Thermal Inspection

Thermal inspection (TI) is a technique for detecting and measuring variations in the heat emitted by various regions of a structure or piece of equipment and transforming them into visible signals that can be recorded photographically. In general, thermography detects surface temperature variations or responses to induced thermal contrast. Anomalies of thermal conditions, such as being warmer or colder than they should be, are taken as alarm signals of potential problems within the system. Thermography is an effective method for detecting abnormal or defective machinery conditions and thermal profile of a machinery component can, if interpreted correctly, facilitate valuable information on the operating conditions of that component. Thermographic techniques are most appropriate to detect problems found in systems that rely on heat transfer or retention. Essentially, the value of TI has been already accepted in the examination of electrical and mechanical systems and structures. TI can substitute electrical or mechanical examinations with competitive costs and thus, it can be effectively used as a predictive maintenance tool.

6.11.1 Conception

Thermal inspection or, more specifically, infrared thermography (IRT) is one of the most commonly used NDTs for condition evaluation of electrical, mechanical and structural assets in industry [399]. The term infrared (IR) simply means 'below the red' and refers to radiation situated outside the visible spectrum at its red end (i.e. wavelengths from 700 nm to 1 mm). Infrared wavelength emissions are found on the electromagnetic spectrum, between visible light and radio waves. All molecular objects that have a temperature above absolute zero emit infrared radiation in proportion to their temperature. IRT is the technology of measuring components' infrared energy emissions using infrared thermographic instruments and tools [183]. It measures the level of infrared radiation and alters this information into an actual temperature reading. IR thermographic equipment detects the infrared radiation from the target object and converts it into an electrical signal; the equipment's electronics then amplify and process the signal. Afterwards, this signal can be displayed in various video formats through a monitor as a full object image. The information can then be captured and stored for later analysis [397].

The Electromagnetic Spectrum

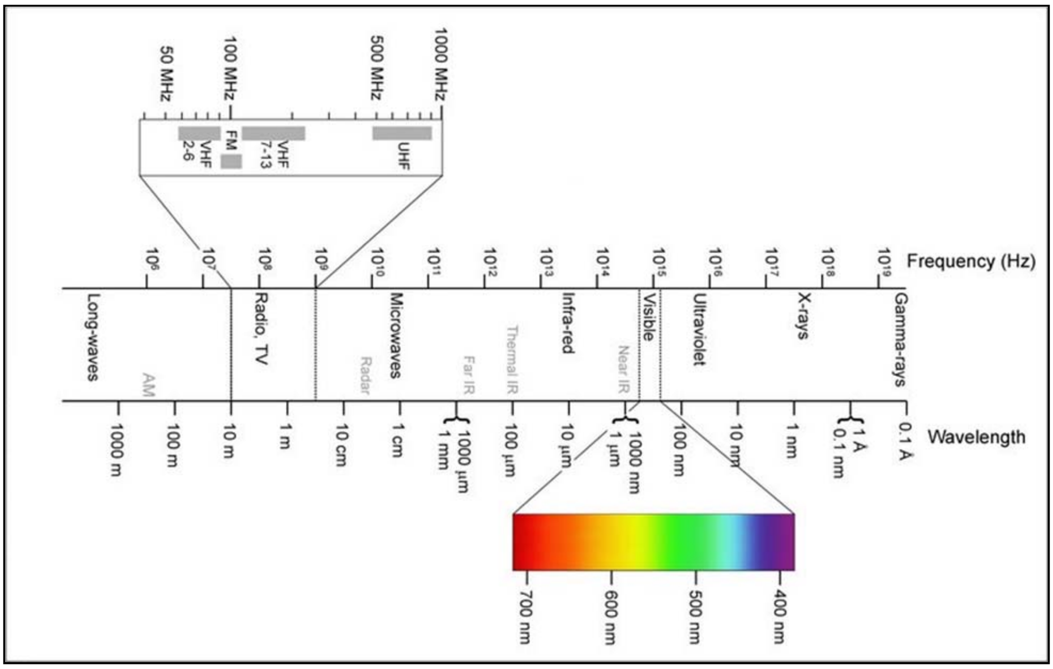


Figure 169 A picture representing the characteristics of the electromagnetic spectrum [WS26]

Rastogi and Inaudi express that TI is technically employed along two schemes, passive and active. The passive scheme inspects materials and structures which are naturally at different (i.e. higher or lower) temperature than ambient [505]. For the active scheme, on the other hand, an external stimulus is required to induce relevant thermal contrasts which are not available otherwise (i.e. the test object has uniform temperature prior to testing).

1. *Passive Thermography:* This thermographic scheme is the simplest thermal inspection method which is widely used for different industrial applications. This is a process in which thermographic appliances (e.g. thermometers or cameras) convert the self-generated thermal energy (i.e. heat) of a specimen to viable qualitative and quantitative information. For this purpose, usually thermographic cameras are preferred. With use of thermographic cameras, TI can be seen as the process of generating visual images that represent variations in IR radiance of surfaces of objects. By using a device that contains detectors sensitive to IR electromagnetic radiation, a 2D visual image reflective of the IR radiance from the surface of an object can be generated. The image shows variations in radiance which are displayed as a range of colors or tones. As a general rule, objects in the image that are lighter in color are warmer and darker objects are cooler. Even though the detectors and electronics are different, the process itself is similar to that a video camera uses to detect a scene reflecting electromagnetic energy in the visible light spectrum, interpreting that information, and displaying what it detects on screen which can then be viewed by the device operator [635].

2. *Active Thermography:* This is scheme involves heating the surface of an object using an external heat source and observing how temperature decays with time. In other words, it substantially means that the solid body is artificially heated in order to obtain temperature differences that can be detected with thermographic systems. Discontinuities in the material are identified by variations in the temperature decay rate. Besides, since characteristics of the required external stimulus are known somehow such as the initially time of application, a more reliable and accurate quantitative characterization becomes possible [505]. There exist various types of active thermography and thermal stimulation which are brief as followings.

- *Pulsed Thermography:* In this case, the specimen under inspection is placed immobile in front of the infrared camera and a pulse of energy is brought to the object launching a thermal front that propagates under the material's surface. This pulse of energy can be generated by mean of lamps, flashes, laser beam, and air or water jets [397], [400]. It has to be underlined that that a warm or a cold stimulation is possible since what matters is the generation of a temperature differential [131]. The duration of the generated pulse is variable from µs to s depending on the thickness of material under inspection and its thermal properties such as the thermal conductivities. The behavior of the specimen is then recorded and analyzed either during the rising surface temperature or during the decay [17], [131], [393]. The quantitative analysis is also possible and is generally based on thermal contrast images which are recorded either through the whole evolution or at the temperature peak [234], [341], [399]. The merits are the ease of use in the field and fast procedure due to operating in a pulse-transient regime, but a demerit is the required prior knowledge in analysis of the recorded images [398]. Pulsed thermography is influenced by local variation of emissivity and non-uniform heating that masks the defect visibility. To overcome the second effect Grinzato et al. adopt a linear motion of the source at constant speed which is referred to as lateral heating thermography [235].

- *Transient Thermography:* This method is used for the detection of deep-seated defects in materials with low temperature conductivity. The specimen is heated up over a long period of time in a furnace at a nondestructive temperature (e.g. 50°C). Afterwards, it is brought into a normal climate and at the same time the variation of surface temperature is recorded with an infrared camera. Because the sample is losing heat to the environment due to convection and radiation, the surface is cooling down. Heat is flowing from the inside to the surface of the sample. A defect, typically a delamination or a cavity, is a thermal barrier for the heat flow. This leads to an inhomogeneous temperature distribution on the surface, which is detected by the infrared camera. Only a lap is required for the measurement (i.e. from the defect to the surface); thus, the heat has to cover only half the distance compared to other thermal methods in which require two laps (i.e. going and coming back). This explains why it is possible to detect deep-seated defects in short time with this method [17], [29].

- *Step Heating Thermography:* In this technique, which is also known as long pulse thermography, the increase of surface temperature is monitored while applying a step heating or long pulse. This contrary to pulsed thermography for which the temperature decay is of interest after the use of the heat pulse. Here variations of surface temperature with time are related to specimen features and this cause the technique sometimes to be called time-resolved infrared radiometry (TRIR). Step heating thermography has different particular applications such as coating thickness evaluation including multi-layer coatings and thermal conductivity examination in electronics [393], [394].

- *Modulated Thermography:* This technique, which is also known as lock-in thermography, is based on generation of thermal waves inside the specimen that is submitted to a sine-modulation heating at a fixed frequency introducing highly attenuated and dispersive thermal waves. The resulting oscillating temperature field is remotely recorded through its thermal infrared emission with the infrared camera. The lock-in terminology refers to the necessity of monitoring the exact time dependence between the recorded temperature signal and the reference signal which is the sine-modulated heating. This can be done with a lock-in amplifier in a point by point laser heating or by other means [102]. This technique is more commonly used for inspection of polymer materials [101]. In comparison with pulsed thermography, modulated thermography provides better depth resolution which can be tuned depending on the modulation frequency plus it is insensitive to specimen's surface artifacts. On the other hand, it has a more complicated set-up due to the need for depositing modulated heating on the full field view of the specimen. This technique is relatively slower in acquisition process, but provides images with higher resolution than of the pulsed thermography [34], [35], [102], [670].

- *Pulse Phase Thermography:* This approach was introduced for thermographic NDE applications as an interesting signal processing technique [398]. It combines somehow the pulsed acquisition procedure of the pulsed thermography with the phase/frequency concepts of lock-in thermography for which specimens are submitted to a periodical excitation [277], [401]. Similar to pulse thermography, the object under inspection has to be positioned motionless below the infrared camera and, in order to excite the temperature signal on the surface, a fast acting heat source, e.g. flash light, has to be imposed on the sample. The basic idea of pulse phase thermography is to acquire a temperature tri-dimensional matrix (i.e. temperature profile), similar to pulse thermography, and to process in the frequency domain, applying a Fast Fourier Transform (FFT) algorithm. Mathematically, a pulse can be decomposed into a multitude of individual sinusoidal components. In that respect, when a specimen is pulse heated, thermal waves of various amplitudes and frequencies are launched into the specimen in a transient mode. Going back and forth between temporal and frequency domains is possible via FFT. The defect maps can be obtained as results of magnitude and phase of specific frequencies of the Fourier Transform of temperature after a transient heating. Therefore, pulse phase infrared thermography combines the advantages of both pulse infrared thermography and modulated infrared thermography [402].

- *Microthermography:* This method, which is also known as high-resolution photo-thermal imaging or hot spot detection, has been well known in principle but was introduced as a NDT only about 1990. This method gives information about a material's near-surface properties. Winschuh et al. explored the applications of microthermography with the Aladdin thermo-microscope [666]. Using a modulated laser bead as a periodic heat source, a thermal flux is produced that propagates into the material's surface. The propagation can be described by a thermal wave mode. Changes in the thermal properties of the material influence the propagation behavior of the heat. As a result, this also changes the surface temperature of the material. Therefore, by observing the infrared radiation re-emitted from the material's surface, information can be collected about the material's properties, microstructure, and defects. Due to the nature of the thermal diffusion process and the narrowband signal processing, selection of a certain penetration depth by selecting a modulation frequency strongly influences the measurement times required [268], [327].

- Vibrothermography: It is a special technique that utilizes a combination of mechanical vibrations and real-time video-thermography to investigate the internal state of damage in materials. Under the effect of mechanical vibrations or acoustic waves induced externally to the structure, direct conservation from mechanical to thermal energy occurs and heat is released by friction precisely at locations where defects such as cracks and delaminations are located [606]. Nevertheless, this technique is unique in its ability to characterize complex damage states, such as development of fatigue in composite materials, in a manner which is directly related to the mechanics of the defect formation and of the defect state. Because of this, vibrothermography can be deployed for quantitative nondestructive measurement of the severity and distribution of defects and damage states [265], [266]. Conceptually, the mechanical energy is converted to thermal energy due to the acoustical damping. The defected regions have a stronger damping and also a stress concentration next to them, both of which result in a higher temperature generation. Because of the changes of the thermal properties, the defects also affect the heat conduction.

These phenomena result in thermal anomalies that can be observed and recorded via a thermographic camera or video recorder. The suitability of this technique has been proved for different composites and polymers. Its typical applications are in detection of impact damages, inclusions, voids, and cracks, and the evaluation of stress level distributions, paint thicknesses, and quality of bondings [503]. Vibrothermography has the potential to facilitate extremely sensitive detection of small, tightly-closed cracks, and to inspect large structural areas that are undetectable using other thermographic methods. However, development and implementation of an inspection procedure requires advanced knowledge and training [551].

6.11.2 Tools and Techniques

There exist different thermographic measuring appliances which have an operating temperature range of between -20°C and +1500°C and a sensitivity of 0.1°C, enabling well-trained operators to detect even the most minor deviations in the temperature-based machinery condition. These detection devices can be mainly categorized into detectors, thermometers and cameras.

Detectors in this field come in large variety of forms and different levels of sophistication but on the whole they are either thermal detectors or photon detectors which are also known as quantum detectors. Function of thermal detectors consists of a two-step process in which the absorption of thermal energy raises the temperature of device that afterwards changes some temperature-dependent parameters. They are often used for point or localized measurement in a contact or near contact mode. Thermal detectors use the infrared energy as heat and their photo sensitivity is independent of wavelength. Advantages of thermal detectors are that the element does not need to be cooled and they are comparatively low in price that make them to be the most commonly used radiation thermometer detectors [548]. However, their response time is relatively slow and their detection capability is low. Thermal detectors can be grouped to thermocouples, thermopiles, bolometers, and pneumatic and pyroelectric detectors, which are usually made of lead–zirconium titanate - PZT, triglycene sulphate - TGS, and lithium tantalite - LT [248].

In contrast, photon detectors convert incoming photons directly into an electrical signal. Photon detectors release electric charges in response to incident radiation. In lead sulfide and lead selenide detectors, the release of charge is measured as a change in resistance. In silicon, germanium, and indium antimonide, the release of charge is measured as a voltage output. The response time and sensitivity of photonic detectors are quite higher, but usually they have to be cooled to cut thermal noise (except for detectors used in the near infrared region) plus they have a maximum wavelength beyond which they will not respond.

Although the cooling process may be considered as a significant demerit in the application of quantum detectors, but their superior electronic performance still makes them the detector of choice for the bulk of thermal imaging applications. Some systems can even detect temperature differences as small as 0.07°C [548]. Quantum detectors are grouped to intrinsic (i.e. photoconductive and photovoltaic) and extrinsic types which are made of a large variety of materials with different spectral responses and operating temperatures [248].

Here the term intrinsic stands for intrinsic semiconductor, also called undoped semiconductor, which is pure semiconductor without any significant dopant species present. The number of charge carriers is therefore determined by the properties of the material itself instead of the amount of impurities. On the other hand, extrinsic type refers to semiconductor which has been doped, that is, into which a doping agent has been introduced, giving it different electrical properties than the intrinsic (pure) semiconductor. The term photoconductive denotes the detectors, the materials of which become more conductive with the absorption of electromagnetic radiation such as infrared light. The term photovoltaic refers to detectors on which photoelectric current appears upon illumination (i.e. direct conversion of light to electricity); table 47 provides more detailed information. Thermometers, in the world of thermography, identify an object’s temperature based on IR emissions. If a laser beam is employed to enhance aiming the device, the term ‘laser thermometer’ would be used. These devices do not provide any image representing an object’s thermal profile, but rather a value indicating the temperature of the object or the area of interest on that object.

Table 47 Different types of quantum IR detectors and their characteristics [248]

Quantum Detectors Type		Detector Material Type	Spectral Response [µm]	Operating Temperature [°K]
Intrinsic	Photoconductive	*PbS* - Lead sulfide	1.00 to 3.60	300
		PbSe - Lead Selenide	1.50 to 5.80	300
		InSb - Indium antimonide	2.00 to 6.00	213
		HgCdTe - Mercury cadmium telluride	2.00 to 16.0	77
	Photovoltaic	*Ge* - Germanium	0.80 to 1.80	300
		InGaAs - Indium gallium arsenide	0.70 to 1.70	300
		InAs - Indium arsenide	1.00 to 3.10	77
		InSb - Indium antimonide	1.00 to 5.50	77
		HgCdTe - Mercury cadmium telluride	2.00 to 16.0	77
Extrinsic		*Ge:Au* - Gold-doped germanium	1.0 to 10.0	77
		Ge:Hg - Mercury-doped germanium	2.0 to 14.0	4.2
		Ge:Cu - Copper-doped germanium	2.0 to 30.0	4.2
		Ge:Zn - Zin-doped germanium	2.0 to 40.0	4.2
		Si:Ga - Gallium-doped silicon	1.0 to 17.0	4.2
		Si:As - Arsenic-doped silicon	1.0 to 23.0	4.2

There exist varieties of IR thermometers for in industrial applications, including configurations designed for flexible and portable handheld use, as well many designed for mounting in a fixed position. Among all, the spot infrared thermometer - also known as infrared pyrometer - which measures the IR radiation at a spot on an object's surface is the most commonly used for industrial applications. An IR thermometer is consisted of an optical system to collect the energy emitted by the target, a detector to convert this energy to an electrical signal, an emittance adjustment to match the thermometer calibration to the specific emitting characteristics of the target, and an ambient temperature compensation circuit to ensure that temperature variations inside the thermometer due to ambient conditions do not affect accuracy. It is essential to underline that the terms emittance and emissivity are often used interchangeably. Emissivity refers to the properties of a material; emittance refers to the properties of a particular object. In this latter sense, emissivity is only one component in determining emittance. Other factors such as object's shape and surface finish must be taken into account.

Spot IR Thermometers

Figure 170 Two different spot infrared thermometers; for such handheld devices, generation of accurate information depends on right targeting of the device [WS33], [WS40]

The last but not least category of thermographic appliances are thermographic cameras, which are simply devices that make an image using infrared radiation similar to ordinary cameras that capture an image using visible light. The major difference is that instead of the 450–750 nm range of the visible light cameras, infrared cameras operate in wavelengths as long as 14,000 nm (i.e. 14 µm). At the fundamental level, IR cameras can be classified into two main groups of IR imagers and cameras with radiometric capability. A simple IR imager is capable of detecting an object's IR emissions and translating this information into a visual image. It does not have the capability to analyze and quantify specific temperature values. This type of IR detection device can be of use when temperature values are unimportant and the object's temperature profile (represented by the image) is all that is needed to define a problem. An example of such an application would be in detecting missing or inadequate insulation in a structure's envelope. In the same way, IR cameras with full radiometric capability detect the IR emissions from an object and translate this information into a visible format as in the case of an imager, plus they have the capability to analyze the image and provide a temperature value corresponding to the area of interest. This capability is useful in applications where a temperature value is important in defining a problem or condition.

Sample Thermal Images

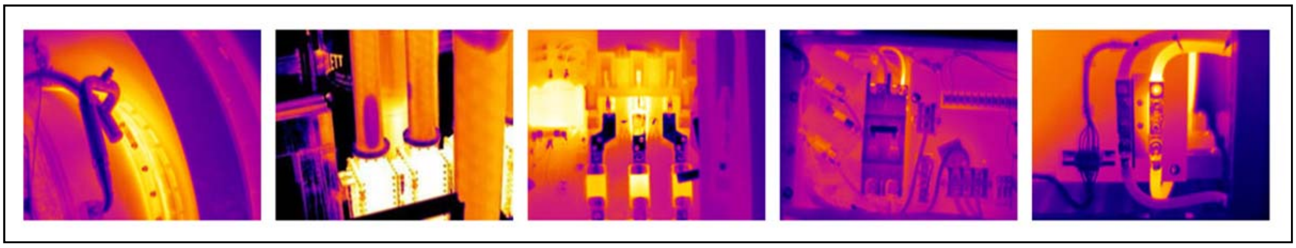


Figure 171 Thermal images from left to right show: an exhaust leak on a power turbine near the exhaust cone, outer delaminations of process pipes, a disconnected fuse in the middle, abnormal temperature deviation in a UPS inverter, abnormal temperature deviation in a rectifier cabinet [WS63]

Technically, thermographic cameras can be classified into two main groups based on their detectors type which can be cooled or uncooled. Cooled detectors are typically contained in a vacuum-sealed case and cryogenically cooled. This greatly increases their sensitivity since their own temperatures are much lower than that of the objects from which they are meant to detect radiation. Uncooled thermal cameras use a sensor operating at ambient temperature, or a sensor stabilized at a temperature close to ambient using small temperature control elements. Modern uncooled detectors all use sensors that work by the change of resistance, voltage or current when heated by infrared radiation. These changes are then measured and compared to the values at the operating temperature of the sensor. Uncooled infrared sensors can be stabilized to an operating temperature to reduce image noise, but they are not cooled to low temperatures and do not require bulky, expensive cryogenic coolers. This makes infrared cameras smaller and less costly. However, their resolution and image quality tend to be lower than cooled detectors [471], [568].

Passive thermography, in search of hidden defects or damages in machinery and equipment, together with information on the degradation mechanism, serves as an early diagnostic tool, which completes the inspection techniques utilized for machinery condition monitoring. Passive thermography, while having wide variety of tools, has a simple technique. The camera is simply pointed at the test piece and from the thermal image a temperature map is constructed. Through analysis of the thermal image and/or the temperature map the required information would be attained. Passive thermography is usually preferred over active thermography for inspection of machinery in production and assembly plants. This is due to its ease of use and simpler technique which require less priori knowledge and advance training plus more portability. However, active thermography, which involves heating the surface of the object rapidly using an external heat source and observing how the temperature decays with time, intakes different techniques and methods of implementation that have been reviewed briefly in the previous section. Still, the choice of most appropriate active thermography technique depends on several considerations linked to material characteristics and test objectives.

Among all the most commonly used active thermography techniques: pulsed thermography can provide information about size, depth and thermal resistance of defects by processing signals. Data may be impinged on by local variation of thermal emission and non-uniform heating which can mask the defect visibility. Improvements on surface temperature distribution may be attained by using the lateral heating thermography, but in this case, advance knowledge of thermal properties of materials under the test for suitable values of lamp speed and heating exposure is required. Transient thermography has the benefit of rapidly inspection of large areas for surface or near surface defects and that it produces easily interpretable results. However, its disadvantage is that its success is highly dependent on defect depth and size, which restricts its application to near surface defect imaging [18]. In modulated thermography, information about size, depth and thermal resistance of defects are achieved without troublesome post-processing procedures. In addition, due to its insensitivity to non-uniform heating and local variation of the emissivity coefficient, it is has unique applications for inspection of heat-sensitive objects. Its main limitation lies in the available frequencies for the heat flux modulation which are not sufficiently low to detect deeper defects. Pulse phase thermography combines advantages of both pulsed and modulated techniques; the surface is heated in pulse mode and results presented in terms of phase (amplitude) image, and it helps resolving limitations of the previously described techniques. However, its main demerit is the increase of the object surface temperature which cannot be very low as in the modulated thermography since in this case each frequency is tested in the transient regime and a certain temperature difference between two successive images is needed [110], [398].

Although different active thermography techniques have their own setup and process settings, but these have many components in common. Here, as an example, a case of pulsed phase thermography in which flash lights are used as source of heating is taken. In this case, first, the test object's surface is stimulated with a thermal pulse in either transmission or reflection mode depending on the application. Then, the thermal decay is monitored at the surface where defective zones will appear at higher or lower temperature with respect to non-defective zones on the surface, depending on the thermal properties of both the material and the defect. The thermal signatures are recorded using an infrared camera. A thermal map of the surface or a thermogram is captured at regular time intervals. A 3D matrix is formed, where x and y coordinates are the horizontal and vertical pixel positions respectively, and the z coordinate corresponds to time. The thermogram matrix is then will be processed and analyzed in a computerized system [290].

A Simple Schematic of Pulsed Phase Active Thermography

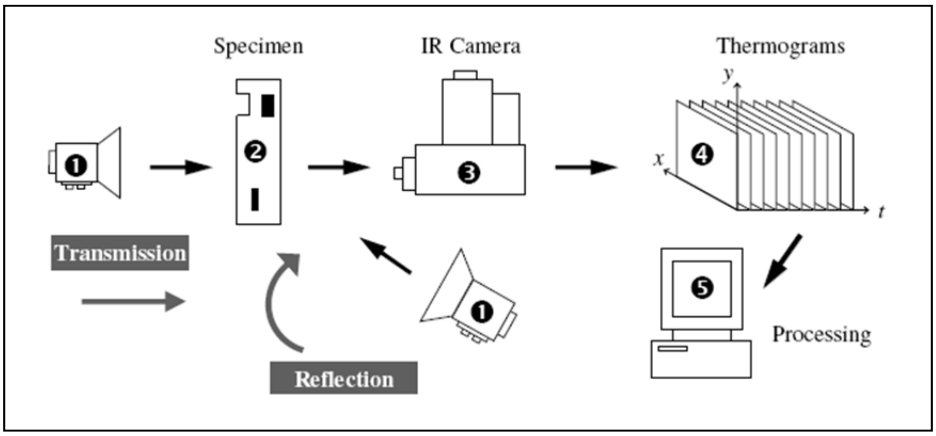


Figure 172 A schematic of pulsed phase active thermography setup and process [290]

In spite of all said and explained, passive thermography (in comparison with active thermography) is the ideal predictive maintenance technique that allows plant maintenance professionals to keep their facilities operating efficiently. A non-contact inspection process, using an infrared camera that represents temperature in a color spectrum image, allows surveys to be conducted with equipment operating normally. Problems can be located, repairs can be scheduled on the basis of the reports and costly shutdowns can be avoided.

For both passive and active thermography what actually has great impact is the correct interpretation of the generated thermal images. Most thermal imagers produce a gray scale video output in which white indicates areas of maximum radiated energy and black indicates areas of the lowest radiation. In order to ease general interpretation and facilitate subsequent presentation, the thermal image is artificially colorized in an automatic way by the device or some software. This is achieved by allocating desired colors to blocks of grey levels to produce the familiar colorized images. It enables easier image interpretation to the untrained observer. Additionally, by choosing the correct colorization palette the image may be enhanced to show particular energy levels in detail. Many thermal imaging applications are qualitative in nature. Nevertheless, the effects of the sun, shadows, moisture and subsurface detail must all be taken into account when interpreting the image. However, great care must be exercised when using an infrared imager to make quantitative temperature measurements. The amount of infrared radiation emitted from a surface depends partly upon the emissivity of that surface and emittance of the object, hence, accurate assessment of these factors is required.

6.11.3 Use and Applicability

Infrared thermography is perhaps one of the most effective diagnostic techniques for early detection of equipment faults. All objects emit thermal energy and the infrared imaging system converts it into images. Through expert analysis these images one can reveal defects or problems areas in electrical systems, mechanical equipment, building envelopes, or any process that uses or produces energy [377]. Thermal imaging was originally forged and used in the steel industry to monitor the condition of blast furnace linings, stoves, steel mixing vessels and electrical machines and equipment [609]; however, later it has been employed in other sectors.

The basic premise of thermographic NDT is that the flow of heat from the surface of a solid is affected by internal flaws such as disbonds, voids or inclusions. Thermal imaging systems are commonly used to inspect a wide variety of materials. These systems can scan a large area in a short period of time. The imaging system functions much like a video camera and the thermal profile of the observed area can be viewed through the instrument's optics. A thermal image can also be generated by heating the far side of an object while monitoring the opposite surface for cold spots where heat flow is impeded by flaws. This through-transmission approach improves the depth sensitivity; however, the method is more sensitive to near-side flaws rather than defects at depth [360].

IR thermometers are designed to measure the surface temperature at a single point on a machine surface. They can be used to monitor the temperature of critical parts of plant machinery, such as bearing cap and motor winding, and to spot-check process piping system. Besides, the thermograms and thermal images taken with an IR camera measure or indicate the temperature distribution at the surface of the object. Thus, the presence of discontinuity in engineering components or systems that have an effect on the temperature distribution on the surface can be detected accordingly. Leakages in plant components, short circuit, degradation of electrical contacts and terminations, and later stages of bearing failure that lead to overheating can be easily detected by this method [36], [296].

Generally, there are four basic areas where IR thermography can be used for nondestructive condition evaluation: electrical, mechanical (including oil and gas, refractory and steam systems), and structural systems (e.g. buildings and water installations) plus cryogenics that are the branches of physics and engineering that involve the study of very low temperatures, how to produce them, and how materials behave at those temperatures. Regarding the condition based maintenance of machinery and equipment in industry the first two categories are naturally major points of focus. Applications for infrared testing include locating loose electrical connections, failing transformers, improper bushing and bearing lubrication, overloaded motors or pumps, coupling misalignment, and other applications where a change in temperature will indicate an undesirable condition. Since typical electrical failures occur when there is a temperature rise of over 50°C, problems can be detected well in advance of a failure. Followings are intensive but compacted research results of different applications of infrared thermography in industry.

- *Applications in electrical systems:* From a thermographical point of view, faults in electrical systems often appear as hot-spots which can be detected by thermal detectors, thermometers and IR cameras. Hot spots are often results of increased resistance in a circuit, overloading, or insulation failure. One the most common types of fault found on electrical components are defective contacts due to poor installation, e.g. screw connections that are over-tightened or under-tightened. Fluctuations in the electrical load and the resultant expansion or contraction of joints are another common cause of poor connections. A poor contact usually produces an increased electrical resistance. The ensuing power drop generates an increase in temperature in the area of the connection, which will continue to increase as the contact deteriorates. Initially the heat generated can be conducted away from the origin of the fault along the path of the circuit but as more and more heat is generated the temperature will continue to increase until eventually the component fails. If the temperature rise is not detected, there will be an unanticipated disruption of the electrical power supply at least, possibly even a fire loss. Use of passive IR thermography in this field involves inspection of power systems, electrical connectors, electrical distribution systems, electronic circuits and other objects which are listed in the next page.

  The electrical and electronic objects which can be inspected by passive thermography are many; though, the most commonly inspected equipment and machinery in industry are: power transformers (fins, clamps), transmission lines (splices, shoes and end bells, insulators), distribution lines and systems (splices, line clamps, switches and breakers, capacitors, pole-mounted transformers, lightning arrestors, bus connectors), generator facilities and motors (connectors, windings), switches, switchgears, buses, fuses, relays, capacitors, cable trays, batteries and charging circuits, and power and lighting panels. The problems which can be detected by passive IR thermography regarding the electrical and electronic objects are also very broad, but they can be summarized as: overheating, inductive heating problems of electrical lines, crack or damage of insulations, poor contacts and disconnections, and other internal and external problems regarding windings and bushings in electrical systems [217], [360], [432], [590].

Passive IR Thermographic Inspection of Electrical Systems

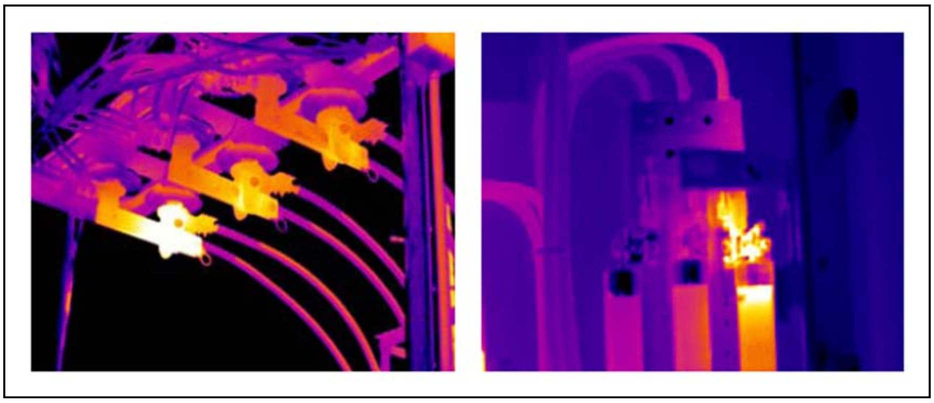


Figure 173 Application of passive IR thermography for electrical systems; from left to right: a poor connection in a power distribution system, a faulty connection on top of a fuse [360]

- *Applications in mechanical systems:* According to Smith, from a maintenance perspective, thermography is specifically well-suited for sensing undue heat generated by excessive friction in misaligned or faulty rotating components of mechanical equipment [572]. Thermography enables measurements to be taken on very hot, very cold, voltaged or inaccessible items with high precision (i.e. up to ± 1°C) and very high temperature resolution (e.g. 0.1°C). The measurements are taken in real time with up to 600 images per second and do not affect the process or the item. Subsequent evaluation allows conclusions to be made about the quality of the machinery components.

  Infrared thermography has broad application fields in examination of mechanical systems. To illustrate, one may consider the following cases: In the majority of bearing failures in rotating equipment, the increase in noise or vibration levels that occurs before the loss happens is preceded for some time by an above-normal rise in temperature. If this is detected at an early stage, damage can be reliably averted. Damage to the cylinder heads of piston compressors is often the result of valve assemblies overheating because of defective valve springs or plates. If thermographic inspections of critical areas are carried out at regular intervals, impending damage can be identified in good time. By means of thermographic inspections, operators can detect and assess the level of scale build-up on the inside of pipelines. This makes it possible to determine the best time for removing the scale.

  Similar to the case of electrical systems, there exist wide varieties of mechanical objects that can be inspected by thermographic techniques; though, the most commonly inspected equipment and machinery in industry are: bearings, gears, gearboxes, drive belts, couplings, shafts, pumps, pistons, valves, tanks, pipes, steam systems (boilers, tubes, nozzles, traps, lines), heaters, heat exchangers, compressors, turbines, furnaces, fans, ventilation systems, rotary kilns and industrial dryers. The problems which can be detected can be listed as: overheating, misalignments, imbalances, pipeline blockages, problems related to faulty couplings, and leakages [213], [217], [360], [590].

Passive IR Thermographic Inspection of Mechanical Systems

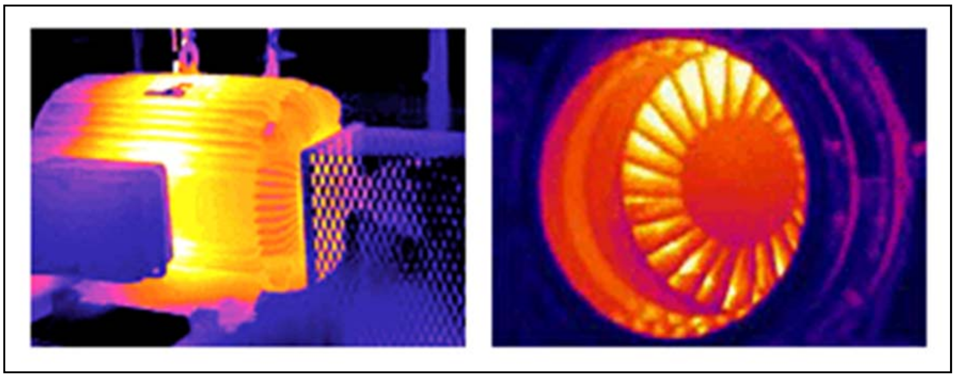


Figure 174 Application of passive IR thermography for mechanical systems: Rotating machines create heat; excess heat usually means a problem. It damages belts or bearings but these can be easily found by thermography [WS94]

Besides the mentioned applications, passive and active infrared thermography techniques have other special applications in different industries that can be named as: Inspection and analysis of water and air discharge patterns, inspection of conveyer belt rollers (i.e. if they are seized), improper lubrication of bearings [590]; detection of fluid levels in vessels, containers and tanks, fluid flow investigations in pipes and lines and through valves, efficacy inspection of insulations and refractory systems [213]; analysis of welding processes [14]; analysis of thermal stress in tensile materials [127]; scanning of fatigue in metals [391]; measurement of porosity in composite materials [135]; and, various applications for inspections of building structures such as inspection of roof and wall envelops [590], [616]. Thermography can also be employed to detect flaws in materials or structures. In case of existence of disbonds, voids or inclusions, the heat flow is influenced. Sound material, a good weld, or a solid bond lets heat dissipate rapidly through, whereas a defect retains the heat for longer time [556]. IR techniques can be practically used to detect material thinning and corrosion of relatively thin structures as areas with different masses absorb and radiate heat at different rates [639]. Coatings on materials such as metals, plastics, ceramics, alloys and composites are extremely important in manufacturing. Although, the quality of coatings has been improved over the years, there is still a need for reliable NDT techniques to assess the quality and test the integrity of theses coatings. This is one of the areas in which thermography, more specifically microthermography, has been frequently employed in research and development [188], [666].

Table 48 Potential component based problems that can be identified by TI [39]

Component	Detectable Problem	Component	Detectable Problem
Wire	Cut, corrosion under insulation	Klin	Refractory damage
Motor	Overloading, failing bearing and brush	Boiler	Refractory damage, blocked tube
Circuit	Uneven loading, short circuit	Bearing	Poor lubrication, overheating
Roofing	Moisture/insulation damage	Lighting	Faulty ballast operation, overheating
Steam valve	Leak, defective trap	Structure skin	Corrosion, material thinning
Thermal sealing	Even heat distribution	Heat exchanger	Abnormal thermal patterns
Power transmission	Poor connection, broken insulation	Building envelope	Poor/damaged insulation
Die-cast/mold equipment	Abnormal thermal distribution	Electrical connection	Resistance due to faulty connection
Propeller/ventilation blade	Crack, corrosion	Chiller/air-conditioning unit	Leak, abnormal cooling patterns

6.11.4 Limitations and Pros

Infrared thermography is a deep-seated tool in the armory of nondestructive testing and condition monitoring techniques. There is a wide range of applications in industry and it can be used to investigate a very broad range of situations where variation in surface temperature may represent faulty equipment settings or, indicate a surface or subsurface discontinuity in materials. Another advantage of thermography over other inspection methods is that whereas the latter may require systems under inspection to be shut down to permit safe access and close inspection, this is rarely necessary with thermography, and more specifically with passive thermography.

Definitely, there are many instances where it is necessary for plant/systems to be fully operational to produce the optimum thermal environment for testing. This can again have a significant spin-off in terms of time and cost savings. Whilst, in many situations, thermography can be used as a standalone technique, there are also circumstances where the effectiveness of an investigation can be enhanced by the combination of thermography with other nondestructive testing and condition monitoring techniques. Even though some skepticism exist as to the extent of applicability of thermography, this can often be traced to lack of experience, inappropriate use, poor interpretation and failure to integrate the technique correctly into the overall investigation [616].

In recent years, there have been developments of IR thermography system for fast and reliable detection of hidden corrosion, impact damage, and water entrapment in different materials. Digital or video image recording allows data storage and retrieval. With the id of software packages developed by IR camera manufacturers, users can analyze the data recorded in the field and incorporate it in a computerized maintenance management system. Regular recording of the standard thermal profiles of critical components make it possible to detect changes in temperature and thus identify impending damage in good time.

Infrared thermography is a mature technology. The equipment and techniques can provide extremely accurate, repeatable and reliable data, although their sophistication requires that the operator be well trained. For optimum results, it is important that the engineer responsible is not only experienced in the use of the equipment and interpretation of a thermal image, but is also knowledgeable in the types of materials/construction under investigation and also in the utilization of the best available environmental conditions. There are no substitutes for training and experience. However, it has to be taken into account that the measurement of infrared emissions is very sensitive to variations of ambient conditions, such as the amount of airborne particles. In outdoor use, for example, high winds can reduce the effectiveness of inspection due to surface temperature shear effects. Similarly, rain may lead to surface cooling, thus masking thermal effects from below the surface. Therefore, extra care must be taken to compensate for the effect of such factors in capturing the thermal data [630].

Table 49 Synopsis of thermography

<table>
<tr><td>Pros</td><td colspan="4">▪ No-contact technique
▪ Visual and digital output
▪ Wide range of applications
▪ Large area can be inspected
▪ Fast, reliable and accurate output
▪ Portable and suitable for field inspection
▪ Wide range of materials can be inspected
▪ No part preparation in passive thermography
▪ Little part preparation in active thermography
▪ Capable of catching moving targets in real time
▪ Safe technique since no harmful radiation is involved
▪ Qualitative interpretation of results are relatively easy
▪ Possibility of measurement in areas inaccessible or hazardous for other methods</td></tr>
<tr><td>Limitations</td><td colspan="4">▪ Highly skillful and well-trained operator
▪ Incapable of determining the depth of discontinuity
▪ Equipment and instruments are relatively expensive
▪ Quantitative interpretation of results requires priori knowledge
▪ Unable to inspect a wide thickness range of material under the surface
▪ Natural thermal losses and emissivity and emittance characteristics affect the test results
▪ Unable to detect the temperature if the medium is blocked by glass or polythene materials
▪ In active method, difficult to deposit large amount of energy in short time over large surface</td></tr>
<tr><td>Equipment</td><td colspan="4">▪ Detectors (thermal and quantum), thermometers, cameras and sometimes a data processing system
▪ In the active infrared thermography, a heat stimulus such as a flash light or a laser beamer in required</td></tr>
<tr><td>Discontinuity types</td><td>▪ Void
▪ Crack
▪ Cavity
▪ Pitting</td><td>▪ Fatigue
▪ Erosion
▪ Porosity
▪ Disbond</td><td>▪ Inclusion
▪ Adhesion
▪ Corrosion
▪ Lamination</td><td>▪ Impact wear
▪ Core damage
▪ Delamination
▪ Water entrapment</td></tr>
<tr><td>Discontinuities size</td><td colspan="4">▪ Small to very large discontinuities can be found by different techniques
▪ Vibrothermography is capable of identifying fine and tightly-closed cracks</td></tr>
<tr><td>Relative inspection cost</td><td colspan="4">▪ Equipment costs are comparatively high. The cost of thermography instruments varies depending on their capabilities. A simple spot thermometer can cost from 250 € to 1,250 €. An IR imager without radiometric capability (i.e. ability of absolute measurement of radiant flux) can range from 3,500 € to 10,000 €. A thermographic camera or video recorder with full radiometric functionality can cost from 9,000 € to 30,000 €. Nevertheless, IR thermography has shown a very high ROI for different applications in industry.</td></tr>
</table>

6.12 Tribological Testing

One of the oldest condition based maintenance techniques still effectively in use is that of tribological testing (TT). Basically, tribological testing is used to define three essential conditions related to the machine's lubrication or lubrication system. First is the condition of the oil. Testing is performed to verify lubricant viscosity, acidity, etc., as well as other chemical analysis to quantify the condition of oil additives like corrosion inhibitors. Second is the lubrication system condition to see if physical boundaries been violated causing lubricant contamination. This is accomplished by testing for water content, silicon, or other contaminants through which lubrication system integrity can be checked. Last but not least is the machine condition itself. By analyzing wear particles existing in the lubricant, machine wear can be assessed and quantified. Moreover, TT undertaken and trended over time can supply indication of improperly performed maintenance or operational practices. Introduction of contamination during lubricant change-out, unseemly system flush-out after repairs, addition of inappropriate lubricant, and improper equipment operation are all conditions that have been found by the trending and evaluation of tribological testing data [630]. All in all, tribological testing is not only a method of determining the condition of a lubricant or oil, but more importantly, a very effective method of evaluating the immediate and future maintenance requirements for lubricated machinery.

6.12.1 Conception

Halling's work in the year 1975 defines tribology as the observation of interacting surfaces in relative motion. Halling claims that tribology is derived from the Greek word "Tribos", which means rubbing, and translates into the English language as the science of rubbing [246]. Basically, tribology is the field of study relating to the interface between sliding surfaces. It covers surfaces sliding, rolling or interacting with each other. Therefore, as anticipated, the problems of friction and wear are a fundamental part of this science. With the purpose of hindering the unfavorable effects of wear, friction, and heat generation within mechanical machinery, lubricants are used [78]. The composition of lubricants steers the condition of a system and guides to the development of faults. In the context of Condition Based Maintenance, tribology is a general term cuddling a range of analyses and techniques which examine oil and lubrication condition and it is consisted of three principal methods of contamination, oil, and wear analyses [174], [457], [647].

Technically, most of the wear types of moving systems leading to machinery failure can be attributed to increases in friction due to insufficient or improperly chosen lubricant or other tribological factors. With tribological testing, expensive and unnecessary failures that imperil production can be avoided. TT requires that oil samples are taken of different machinery such as engines, gearboxes, and hydraulic systems which are in operation. Through careful oil analysis, the type and amount of contaminants and component wear particles can be accurately identified, assessment and evaluation of which lead to determining the potential failures due to the wear of the machinery component or the used oil itself. Typical contaminants are water, sand, dust and other materials which come from outside the system. Machinery component wear particles are typically very tiny metal wear elements.

Indeed, the most common tribological tests including oil analysis and Ferrography are used to verify the condition of the lubricant, wear of oil-wetted machinery parts and the existence of contamination. Oil condition is simply determined by measuring viscosity, acid number, and base number. Additional tests can also be used to identify the presence and/or effectiveness of oil additives such as anti-wear additives, antioxidants, corrosion inhibitors and anti-foam agents. Machinery component wear can be resolved by measuring the amount of wear metals such as iron, copper, chromium, aluminum, lead, tin, and nickel. Interestingly, raises in particular wear metals denote a specific part is wearing, or wear is taking place in a particular part of the machine. Contamination is identified by measuring water content, specific gravity, and the level of silicon. This is due to the facts that often changes in specific gravity mean lubricant has been contaminated with another type of oil or fuel, and the existence of silicon is an indication of contamination from dirt [590].

Whilst inherently good properties of lubricant base oils, sometimes they have to be enhanced to suitably meet the challenges of different industrial applications. Besides, base oil may have some adverse characteristics which need to be lessened or eliminated. Additives are employed to maximize the base oil's desirable properties and minimize its undesirable characteristics or even add new properties. Lubricant additives can be broadly categorized as being either chemically active or chemically inert. Chemically active additives such as extreme pressure (EP), anti-wear (AW), and rust and oxidation inhibitors (R&O) have the ability to interact chemically with metals (to form a protective film) and with polar oxidation and degradation products (to make them innocuous). Chemically inert additives or polymers are used to improve the physical properties that are critical to the effective performance of the lubricant. These types of additives can act as foam inhibitors, viscosity improvers, pour-point depressants, etc.

Additives may embrace from less than 1% to over 25% of the composition of a devised lubricant. Typical turbine oil may have only 1% additive while automotive engine oil have around 25% additive. Usually, lubricants for internal combustion applications may have higher additive content than those for industrial applications. Notably, while additives are used to improve the performance of a lubricant for a particular application, they can also introduce unwanted side effects if used in false concentration or in combination with other additives. It is also essential to underline that additives have varying miscibility in different base oils; therefore, pertinent procedures must be undertaken to guarantee that they can entirely dissolve in the base oil and not segregate [305]. In practice, the critical limits for existence of additives are well defined.

However, as a rule of thumb, trends of the additive elements will provide a reasonable judgment for the lubricant quality. For instance, if additives in a lubricant decreases or increases significantly within a certain period of time, this may indicate that the lubricant has either been degraded (through additive depletion) or that a different type of lubricant has been put into the unit. Many effective extreme pressure and anti-wear additives are corrosive to metal. Therefore, lubricants are typically formulated to optimize a balance between extreme-pressure and anti-wear protection, and corrosiveness.

Table 50 Different oil and lubricant additives and their functions [279], [305]

Category of Additive	Function
Alkalinity Improvers	Neutralize acidic products of combustion
Antifoam additives (defoamants)	Break up large surface bubbles and reduce the number of small air bubbles entrained in the oil
Antioxidants (oxidation inhibitors)	Promote long service and storage life
Antiwear additives	Reduce friction and excessive wear when a full fluid lubricating film is not present
Corrosion inhibitors	Protect metal surfaces against chemical attack by water or other contaminants
Demulsifiers	Promote separation of oil from water
Detergents	Control deposit formation
Dispersants	Create a colloidal suspension of particles to prevent formation of sludge, varnish, and deposits
Extreme pressure (EP) additives	Prevent seizure of sliding metal surfaces under extreme pressure (and temperature) conditions
Pour point depressants	Allow lubricant to flow at colder temperatures
Rust inhibitors	Protect metal surfaces specifically against rusting
Tackiness agents	Improve adhesive characteristics of the lubricant in applications where lubricated components tend to loose oil from their surfaces due to their orientation and the effect of gravity or due to centrifugal effects
Viscosity index (VI) improvers	Reduce the lubricants tendency to change viscosity with changing temperature

1. *Contamination Analysis:* Contamination is a common phenomenon for most lubricated mechanical systems and is the most common cause of premature equipment failure. In manufacturing industries, it is generally acknowledged that more than 75% of hydraulic system failures are as a result of contamination. Contamination will cause degradation of the lubricant and acceleration of the wear rate of mechanical systems, particularly when they have higher hardness than the machine elements materials, and when they are relatively large [326]. Chao et al. found that the friction increases with the particle hardness when it approaches that of the surface; as the particle hardness increases, so does the particle's resistance to deformation, a transition of the wear mechanism from adhesion to abrasion is made possible [118].

   Contamination can occur either externally or internally. External contamination come from sand, dirt, fibers and other environmental debris which may enter the oil system via a breather pipe, faulty seals, or failure to replace a protective filler cap. These types of contaminants can sometimes be detected as elevated levels of silicon, sodium, boron or even aluminum. If a silicon-based synthetic lubricant is in use such explanation is not valid for determining contamination. As another example, although sodium and boron sometimes come from environmental contamination, but they can also be contaminants from engine coolants and in conjunction with water and/or glycol, their presence in a lubricant or oil indicates a possible coolant leak. In contrast, internal contamination is typically caused by lubricant degradation and wear debris. High contamination levels can be due to a failed filter and can be proven by taking both upstream and downstream samples. An increase in wear rate of the lubricated parts in the machine can increase both the particle number and size in the oil.

Table 51 Source of presence of different metal particles [590]

Metal		Source of Presence
Antimony	Sb	lube additive
Barium	Ba	additive from synthetic lubricants
Boron	B	lube additive; coolant inhibitor;
Calcium	Ca	detergent dispersant additive; airborne contaminant in some plants; contaminant from water
Lithium	Li	Lithium complex grease
Magnesium	Mg	detergent dispersant additive; airborne contaminant in some plants
Manganese	Mn	steel alloy
Molybdenum	Mo	ring plating; lube additive; coolant inhibitor; grease additive
Phosphorus	P	anti-wear additive (ZDP); extreme pressure additive (EP additive)
Silicon	Si	dirt; seals and sealants; coolant inhibitor; lube additive (15 ppm or less)
Sodium	Na	lube additive; coolant inhibitor; salt water contamination; airborne contaminate; wash detergents
Zinc	Zn	anti-wear additive (ZDP)

In tribological testing terminology silicon and sodium are known as contaminant metals, whereas, antimony, boron, manganese, molybdenum and lithium are known as multi-source metals. Barium, calcium, magnesium, phosphorus and zinc are known as additive metals.

2. *Oil Analysis:* Oil analysis (OA) is looks at the condition or usability of a lubricant or oil. Use of correct oil or lubricant kept under proper condition reduces wear and energy costs considerably. Basically, OA determines the effectiveness of current lubricant or oil by scanning its level of degradation and deviation from its standard quality. Indeed, OA can be a very effective tool in a tribology testing program and includes numerous techniques such as viscosity test to determine oil viscosity degradation, rotating bomb test to determine water content, total acid and base number tests to determine depletion of alkaline reserve or buildup of oil acidity, and API specific gravity test. In addition, Fourier transform infrared spectroscopy is sometimes used in conjunction with the other tests to test physical and chemical changes in the oil. It is important to consider that even under the best of circumstances, a lubricant or oil will eventually degrade. By monitoring its condition, actions can be undertaken to refresh or replace the lubricant before serious machine damage begins.

Table 52 Categories of lubricant base oils [279], [305], [357]

Category	Brief Explanation
Mineral Base Oils	Mineral base oils are widely used in industry and can be further categorized as paraffinic or napthenic. In general, paraffinic oils have a more stable viscosity response to changing temperatures. They have also excellent oxidation stability and are relatively non-reactive. By contrast, napthenic oils perform better at low temperatures and have better solvency. Most mineral oils used in industry are paraffinic; however, a formulated blend of both types may be used to achieve the desired balance of properties.
Synthetic Base Oils	Synthetic base oils comprise a wide variety of fluids that have a broad range of applications and prices. The most commonly used synthetic oils in industry are: Polyalphaolefins (PAO), Dibasic Acid Esters (Diester), Polyol Esters (POE), Polyalkylene Glycols (PAG), Phosphate Esters, Silicones, Alkyl Benzenes and Polybutenes. These have to be carefully chosen based on specific applications.
Vegetable Base Oils	Vegetable base oils are used in applications where food contact and environmental impact are a consideration, but in general such oils are not widely used in industry.

3. *Wear Analysis:* Wear is the inevitable consequence of surface contact between machine parts such as shafts, bearings, gears, and bushing, even in properly lubricated systems. Equipment life expectancies, safety factors, performance ratings and maintenance recommendations are predicated on normally occurring wear. However, such factors as design complexity, unit size, intricate assembly configurations, and variations in operating conditions and environments can make maintenance or repair needs (ordinary or emergency) difficult to evaluate or detect without taking equipment out of service. Modern integrated and automated high-speed machine systems make any interval of down time costly and non-productive. This is why non-interceptive wear analysis techniques are increasingly being applied in the power, process, semiconductor and manufacturing industries. Machine designers and builders are increasingly using wear analysis as a realistic criterion for improvements in products such as compressors, gears, bearings and turbine components.

   Wear analysis provides maintenance crew with direct information about the wearing condition of machines and equipment. Such information is derived from the study and assessment of wear particle shape, composition, size and quantity. Particulate matters in different lubricant or oil samples can be analyzed to identify the type of wear (e.g. rubbing wear, cutting wear and etc.) that has left its clues in the sample. Besides, by measuring the amount of wear metals at set intervals, so called trend analysis, abnormal wear and tear can be detected prior to catastrophic failure. Trend analysis of wear metals reveals defects before they cause failure. An obvious increase in metals making up a bearing can indicate that the bearing is in the process of failing.

   The critical wear limits depend on the specific machinery, its application and its operating environment. Since wear trends and limits can vary from machine to machine, it is generally useful to trend the data statistically. For instance, in case of a gearbox, a system containing a worm-gear setup might generate higher levels of copper from normal wear than you would see in another gearbox that did not contain a copper-alloy gear. The worm gear would then have a higher acceptable alarm limit for copper. Some equipment manufacturers provide specifications for wear metal limits for their units. Wear analysis is very inexpensive and almost all systems can benefit from this test [630].

It is beneficial to express that root causes of wear-out failure include a synergistic combination of the environment, mechanical loads, and surface chemistry. Environmental factors affecting machine life include heat, dust, and water contamination. Mechanical loads can be acceptable or excessive, depending on machine operation, balance, shaft alignment, etc. Surface chemistry for oil wetted surfaces can be benign or under chemical attack, depending on the condition of the lubricant and presence of corrosive fluid contamination. The combined effect of these environment, machine, and chemistry factors results in physical wear. The following list indicates seven basic wear mechanisms which are ranked taking into account the frequency percentage of causing failures:

I. *Abrasive wear* due to particulate contamination
II. *Fatigue wear* due to cyclic loading
III. *Adhesive wear* due to machine design tolerances
IV. *Corrosive wear* due to contamination with moisture and air
V. *Fretting wear* due to chemical attack combined with oscillating motion
VI. *Erosive wear* due to particulate contaminants
VII. *Cavitation* wear due to implosion of bubbles

Table 53 Source of different spectroscopic metal particles in different machinery objects [590]

Metal		Machinery Objects/Parts			
		Engines	Transmissions	Gears	Hydraulics
Aluminum	Al	pistons; thrust bearings; turbo bearings; main bearings	pumps; thrust washers	pumps; thrust washers	bearings; thrust plates
Chrome	Cr	rings; liners; exhaust valves; shaft plating; stainless steel alloy	roller bearings	roller bearings	shaft
Copper	Cu	lube coolers; main bearings; rob bearings; bearings; lube additive; bushings; turbo bearings	bushings; clutch plates; lube coolers	bushings; thrust plates	bushings; thrust plates, lube coolers
Iron	Fe	cylinder liners; rings; gears; crankshaft; camshaft; wrist pins; oil pump gear; valve train	gears; disks; housing; brake brands; bearings; shaft	gears; bearings; shaft; housing	rods; cylinders; gears
Lead	Pb	main bearings; rod bearings; bushings; lead solder	bushings (bronze alloy); lube additive supplement	bushings (bronze alloy); grease	bushings (bronze alloy)
Nickel	Ni	valve plating; steel alloy from crankshaft; camshaft; gears; from heavy bunker-type diesel fuels	steel alloy from roller bearings & shaft	steel alloy from roller bearings and shaft	-
Silver	Ag	wrist pin bushings; silver solder (from lube coolers)	Torrington needle bearings (Allison transmission)	-	silver solder (from lube coolers)
Tin	Sn	piston flashing; bearing overlay; bronze alloy; babbitt metal along with copper and lead	bearing cage metal	bearing cage metal; lube additive	-
Titanium	Ti	gas turbine bearings, hub and blades; paint (white lead)	-	-	-
Vanadium	V	from heavy bunker-type diesel fuels	-	-	-

On the whole, it is the manifest of machinery maintenance that oil is the lifeblood of machinery, hence, must be cautiously maintained. Increased metal concentrations in oils may tell the maintenance personnel about wearing of machinery components or oil contamination with other oils, process chemical or airborne dust. On the other hand, a decrease in concentrations of various additive metals can be detected for top-up purposes. There are some arguments that periodic oil changing is sufficient and such arguments held sway for many years. Conversely, today's obligations on cost minimization and environmental protection encourage maintenance managers to replace oil based on its condition rather than the calendar, clock, or mileage meter.

In cases where good oil is water and/or solid contaminated, filtration and/or water removal (i.e. oil reclamation) can restore the fluid, allowing its reuse. Except when oil additives have been severely depleted, it is usually feasible to restore large volumes of oil. It should be noted that oil reclamation and polishing can extend equipment life, but is not a therapy for abnormal wear due to mechanical problems such as misalignment and fatigue. Although changing or reclaiming the oil can alleviate those problems temporarily, further maintenance is always necessary.

Lastly, it has to be highlighted that tribological testing and vibration analysis employed together has been proven by many researchers and scholars to be very efficient in the condition monitoring of several kinds of machines in various industries. Tribological testing can designate failures in lubrication or wearing phenomena of different machinery parts and equipment earlier than vibration analysis (VA). Tribological testing often provides information about the wearing mechanisms; however, vibration analysis can reveal faults like unbalance or misalignment, which cannot be easily detected by TT unless wearing happens. VA is often more efficient in detecting the exact cause and point of failure while tribological testing is usually more effective in identification of the root cause [44], [104], [475], [476]. Nevertheless, both methods can usually reveal most faults eventually and sometimes each provides complimentary information. Besides, one of the methods is often used to detect the fault and the other is used to confirm the detection [626].

6.12.2 Tools and Techniques

While there exist different independent companies that generally carry out tribological testing, some vendors do supply testing equipment that can be used on-site to examine and characterize oil and lubricant condition, wear particles, and contamination. These devices are usually composed of several different types of test equipment and standards including oil degradation detection sensors [497], plus, viscometers, spectrometers, oil analyzers, particle counters, and microscopes. On-site testing can offer quick verification of a suspected oil problem associated with critical components such as water contamination. Moreover, on-site testing can provide a tool to promptly define lubricant condition in order to determine the most appropriate time to change the lubricant medium. However, for the most machinery, detailed and accurate analysis still requires the services of an independent laboratory unless the on-site TT unit is fully outfitted with hi-tech equipment and experienced technicians.

Contamination analysis can be entirely undertaken through:

- *Crackle Test:* Water is generally an unwanted contaminant in oil and results in lubricant degradation, which accelerates corrosion and the promotion of wear. Increased water concentrations indicate possible condensation, coolant leaks, or process leaks around the seals. Crackle test is one of the several tests with which water contamination can be identified. It simply involves dispensing a drop of oil onto a heated hot plate that is heated to 150°C and by the amount of resultant water bubbling and crackling one can attain a qualitative measure of whether the water is greater or less than 1% (i.e. 10,000 parts per million or ppm) or not. Result of crackle test is in form of a pass or a fail indication [647]. Of course, accurate readings are difficult on emulsified fluids and the test should only be considered as a screening device for industrial hydraulics, gear boxes, compressors, bearing systems or turbines. Sometimes, dean stark distillation test is used instead. This is also a simple water content test which widely used in industry. In this test water is removed from the sample by means of an azeotrope and the results are accurate down to 0.05% (i.e. 500 ppm).

- *Centrifuge Test:* This test is usually employed for quantitative measurement of gross water contamination. Although quick and accurate, it has poor sensitivity at low water levels. Water is usually considered very undesirable in a system; sometimes though, in an environment where a sudden oil leak could pose a serious fire hazard, a water-based, fire-resistant fluid is used. These fluids (e.g. water glycols, invert emulsions, and surface active agents) contain water as a component of the lubricant. In centrifuge test, such water contents can interfere with test and delude the results. Indeed, in the mentioned case, the water content of these fluids must be closely monitored and maintained in order to preserve the fire resistant qualities of the fluids while continuing to provide the required lubrication [132], [647].

- *Chromatography:* This is a technique for separating mixtures into their individual components so that they can be identified and measured. In contamination analysis, chromatographic methods are often used to separate additives from the base oil. In this technique a mixture is dissolved in a mobile phase, which is usually a gas or a liquid, then passed through a column that contains an immobile stationary phase, which is usually a liquid or a solid. The two phases are selected so that the solubility of the components of a mixture is different in each phase. The different components in a mixture distribute themselves between the two phases and therefore pass through the column in different lengths of time [319].

Liquid and gas chromatography, as the two major sub-techniques, have been used, for instance, in determining fatty acids, fatty acid esters, di- and triglycerides, organophosphorus compounds or even polar emulsifiers in oils [244], [358]. Alternatively, chromatographic methods can be used only for separation of analytes and mass spectrometry is used as a detector. In general, different methods of chromatography are useful in identification of additives like nitrite and nitrate, contaminants such as chloride and sulfate, and degradation acids (e.g. glycolate, acetate, formate and oxalate). It is beneficial to state that nitrites and nitrates are metal-protecting inhibitors; chlorides and sulfates are contaminants. Chlorides can come from source water or air leaks, sulfates can come from source water, combustion gas leaks or residual sulfuric acid cleaner. However, both have the potential to form acids. Sulfate can also form scale. Glycolate, acetate, formate and oxalate are a result of the thermal breakdown of ethylene glycol.

To be more precise, liquid chromatography (LC) is good for analyzing nonvolatile and thermally fragile molecules including high molecular weight compounds. Also, it can be a useful tool for purifying both micro-molecules and macro-molecules derived from chemical synthesis or natural processes. Every liquid chromatograph usually includes the following key components: a pump system for solvent delivery, a sample injector, a column or columns, detectors, and a data handling system. Different types of pumps, injectors, columns, detectors and fraction collectors are used together in various configurations, based on the needs of the sample and application. Two of the most important sub techniques of the LC are high performance liquid chromatography or HPLC, and liquid chromatography/mass spectrometry or LC/MS.

In HPLC components are dissolved in a solvent, and then delivered through a chromatographic column to a detector under high pressure. HPLC is a versatile method that can rapidly analyze a wide range of complex mixtures. LC/MS combines the capability of HPLC with mass spectrometry (MS). A mass spectrometer measures the molecular weight of a compound to provide data for both quantitative and qualitative identification. It usually provides greater sensitivity and far more specificity than most other LC methods. Conversely, gas chromatography (GS) is normally used when the sample can be vaporized below 400-450°C. Every gas chromatograph usually includes the following key components: flow controller, a sample introduction device, column, oven, detectors, and data handling system. A powerful and widely used combination is to couple a GC to a mass spectrometer (MS) to form a GC/MS system, which has similar features as LC/MS due to existence of the mass spectrometer.

A Liquid Chromatography System

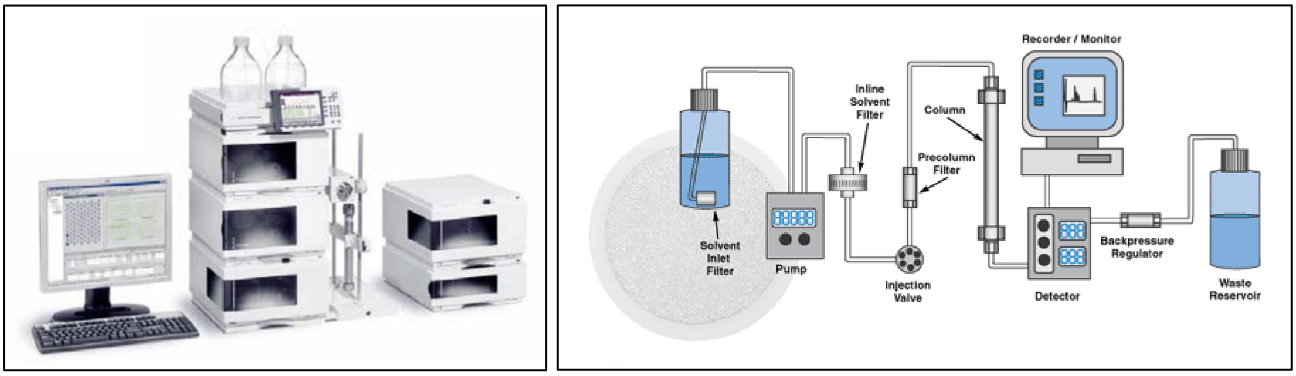
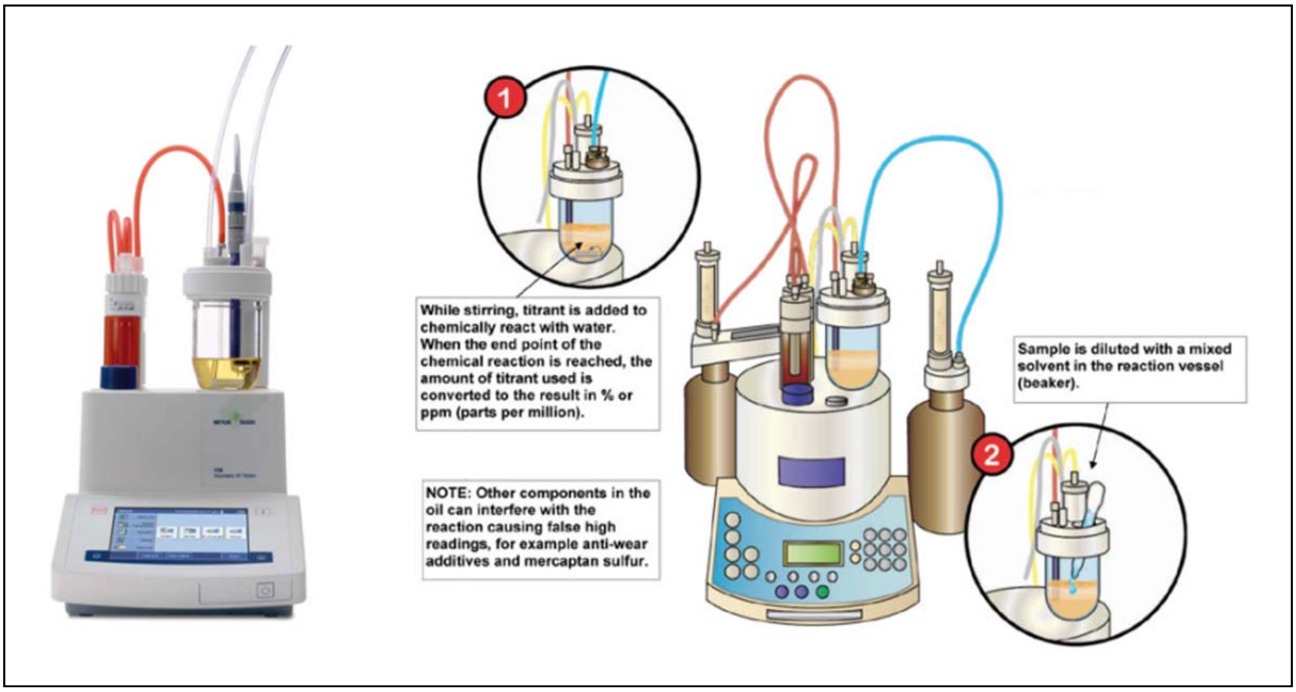


Figure 175 A LC system with purification capabilities and a schematic of such a LC system [WS7], [WS10]

- *Karl Fischer Test:* This is the most commonly used test which quantifies the amount of water in lubricants and oils which not only promotes corrosion and oxidation, but also may form an emulsion having the appearance of a soft sludge. It has the great advantage of good accuracy at low levels of moisture, down to 0.001% (i.e. 10 ppm). Here, one drawback is that skilled personnel are required to undertake it. In this test, water reacts quantitatively with the Karl Fischer reagent. This reagent is a mixture of iodine, sulfur dioxide, bases and methanol. When excess iodine exists, electric current can pass between two platinum electrodes or plates. The water in the sample reacts with the iodine. When the water is no longer free to react with iodine, an excess of iodine depolarizes the electrodes, signaling the end of the test. This test provides very accurate measurements of water content in oil and lubricants [132], [151].

A Karl Fischer Titrator



While stirring, titrant is added to chemically react with water. When the end point of the chemical reaction is reached, the amount of titrant used is converted to the result in % or ppm (parts per million).

NOTE: Other components in the oil can interfere with the reaction causing false high readings, for example anti-wear additives and mercaptan sulfur.

Sample is diluted with a mixed solvent in the reaction vessel (beaker).

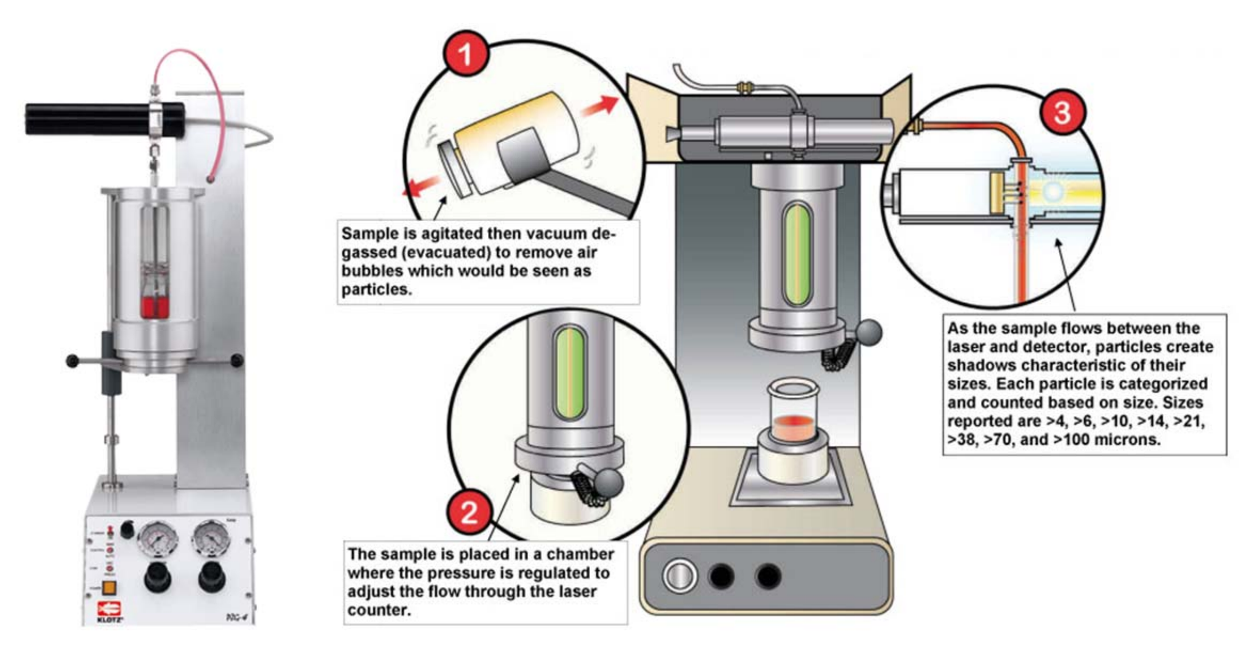
Figure 176 A photo and a schematic of a Karl Fischer titrator [WS4], [WS78]

- *Particle Counting Test:* Particle counting test measures size and quantity of particles in a lubricant and exhibits oil cleanliness and performance. The ISO Solid Contaminant Code (ISO 4406) is an international standard method for classifying the size distribution of solid particles in lubricants and hydraulic oil systems, commonly referred to as a particle count. There are basically three particle counting techniques: manual particle counting which involves use of optical microscopes and can only test some specific oils, automatic particle counting which is suitable for testing turbine oils and hydraulic fluids, and pore-blockage particle counting which is ideal for gear and engine oils. Among all, automatic particle counting is more commonly used in industry. A wide variety of automatic particle counters (APCs) exits for both laboratory and field use and includes both portable data collectors and online instruments [516].

  Although APCs are mostly used for monitoring hydraulic or turbine oils, their application has been extended to gear and other plant machinery, on account of new technologies and analysis techniques. It is essential to underline that significant rise in particle counts can designate many problems such as a failed filter, contaminant entering the system, or start of abnormal wear. Subsequent testings may be required to identify the root cause of higher particle counts [647]. Optical microscopy is often used as a supporting technique for APCs. The quality, morphology, size and color of solid debris can be identified if the oil sample is first filtered through a membrane filter [636]. Scanning electron microscope (SEM) can engender extra information about solid debris as the elemental distribution can be detected from the solid particles on a filter membrane. Nevertheless, SEM is more difficult and expensive to be employed than a normal optical microscope. Besides, such a microscopic analysis also obliges conductive samples for generation of which the membrane filters have to be pretreated, whereas membranes can be studied visually as such in optical microscopy [10], [452], [652].

  As previously mentioned, automatic particle counters intake a wide range of equipment and techniques. One of the mostly used APCs in industry is optical particle counter or OPC, which contains a laser-illuminated optical system that allows single particle sampling by collecting the scattered light from each particle with a solid state detector. Electronics provides amplification of the low level signals received from the photo-detector and converts each scattered light pulse to a corresponding size category, which can be then accumulated in a data logger. Each scattered pulse corresponds to a particle count, and this is incremented in the appropriate size category to obtain particle concentration in a given size interval. The concept of an optical particle counter is shown in the figure 177, in the next page

An Optical Particle Counter



Sample is agitated then vacuum de-gassed (evacuated) to remove air bubbles which would be seen as particles.

The sample is placed in a chamber where the pressure is regulated to adjust the flow through the laser counter.

As the sample flows between the laser and detector, particles create shadows characteristic of their sizes. Each particle is categorized and counted based on size. Sizes reported are >4, >6, >10, >14, >21, >38, >70, and >100 microns.

Figure 177 A photo and a schematic of an optical particle counter [WS37], [WS78]

In general, there are two different ways to count particles in fluids. First is to extract bottle samples from the system and examine the samples in a laboratory or use hand held devices to check any oil sample in the field. Second is to use online particle counters and examine the oil samples periodically or install dedicated onboard particle counting sensors for real time analysis. Of course, both ways bring their own merits and demerits with.

Table 54 Merits and Demerits of Sample and Online Particle Counting

Sample Particle Counting		Online Particle Counting	
Merits	Demerits	Merits	Demerits
▪ Ability to eliminate conditions that may cause error in the use of automatic optical particle counting. One can consider the example of interferences from air or water. ▪ Fluids with high viscosity or extreme contamination can be conveniently diluted prior to counting. ▪ A laboratory offers further analytical possibilities, such as advanced quantitative testing of the contamination or wear debris present.	▪ Elapsed time between sampling and analysis. ▪ Possible erroneous readings of the sample cleanliness due to either contamination introduced during extraction or unclean sample bottles. ▪ Difficult to interpret dynamic changes in the system.	▪ Ease of taking measurements at multiple points on the system during operation. ▪ Most outside influences such as extraneous contamination can be eliminated. ▪ Results can be checked against required cleanliness levels immediately. ▪ Statistical repeatability plus reproducibility of the results can be ensured by the increased number of sequential tests. ▪ Dynamic changes in the system can be measured and used for diagnostic purposes. ▪ Flushing procedures can be monitored to determine when the required cleanliness levels have been achieved. ▪ Possibility to continuously control critical systems. For instance, a turbine bearing's lubrication oil cleanliness can be observed via internet or intranet.	▪ It is generally not possible to perform online particle counts on oil that contains free water or gas, very dirty oil or high-viscosity hydraulic oil. Nor can emulsions or multiphase fluids be measured with any degree of confidence. The stipulations for the viscosity and the particulate level depend on the measurement method.

Nowadays, there are many manufacturing companies of both online and offline OPCs. One of those companies is Internormen Technology GmbH which has its headquarters in Altlussheim, Germany. Internormen produces an online OPC that can be used in mobile or stationary applications and in systems with high-pressure or high-viscosity ranges. Its operation principle is as such: The oil is fed by a small test port, such as a minimess. While performing a count, a cylinder fills up and the oil from the cylinder is forced past a laser sensor by an electric-driven piston. This is to ensure that the volume of oil flowing past the sensor remains constant. The counting is performed in eight different counting channels which are set using a calibration file. The required test volume is 10 ml and the results can be reported in either the number of particles per ml or per sample volume (10 ml). In addition to continuous, single and cyclic measurements, it can examine a bottle sample using an external apparatus.

An Online Optical Particle Counter

Figure 178 Internormen contamination control system, CCS 2, which is an online optical particle counter [WS54]

- *Pentane and Toluene Insolubles Test:* This test separates insolubles from the oil after it has been mixed with pentane and toluene solvents and identifies contaminants in used oil. First, a pentane solvent is mixed in with the oil to lose its solvency for certain oxidation resins (i.e. light yellow to dark brown solid or semi-solid materials composed of carbon, hydrogen and oxygen) and indeed to separate solids and oxidation products from the oil by lowering the viscosity. This dilution also causes the precipitation of such extraneous materials as dirt, soot and wear metals. The mixture is then centrifuged to separate the insoluble material and the insoluble material is measured to determine the percentage of insolubles present. The test is then repeated using toluene instead of pentane. The toluene dissolves organic oxides, but not soot. The mixture is centrifuged again and the insoluble material is weighed. The difference between the two weights of pentane and toluene substances is the estimated soot content in the sample. One of the applications of this test is in evaluation of used oil in industrial engines as common causes of engine oil thickening include highly oxidized oil, glycol contamination, thermal degradation and severe soot contamination [89].

- *NMR Spectroscopy:* Nuclear magnetic resonance spectroscopy is based on the measurement of absorption of electromagnetic radiation in the radio frequency region. The NMR signal is a natural physical property of the certain atomic nuclei but it can only be detected with an external magnetic field. Most modern NMR spectrometers utilize a magnet fabricated from superconducting materials and the magnet winding is cooled with liquid helium. The sample for NMR analysis remains at room temperature. Each isotope of each element in the Periodic Table has a different NMR signal frequency. The most commonly observed nucleus is hydrogen (^{1}H) as found in water (H_2O), although the NMR signal from many other nuclei can be observed with the appropriate hardware. NMR samples are usually liquid solutions contained in glass tubes. NMR solution sample volume ranges from 50ul to 5ml depending on the NMR probe. Sample concentrations of solute for ^{1}H NMR are usually in the range of 100mg to 5g, with 10 to 50mg being typical. The sample is in an intense magnetic field, where the nuclei of atoms form energy states suitable for absorption [569]. ^{1}H and ^{13}C NMR are the basic methods used for characterization and quantitative analysis of different additives, like fatty alcohols, fatty acids, fatty acid esters or antioxidants. ^{31}P NMR is suitable for analyzing organophosphorus additives [128]. 2D NMR methods have also been applied in the quantitative analysis of certain aliphatic components of oils [636].

An NMR Spectroscopy System

Figure 179 An integrated NMR system [WS23]

- *FTIR Spectroscopy:* Fourier transform infrared spectroscopy is a relatively new alternative technique that monitors lubricant degradation (e.g. oxidation, nitration sulfation, additive depletion) and liquid contaminants (e.g. water, glycol, soot, fuel dilution) on the basis of infrared response at certain key wavelengths, and expels the results in absorbance per mm and concentration percentage. In FTIR spectroscopy infrared radiation emitted by the light source is absorbed by the molecules of the sample and the amount of absorption is then detected and analyzed.

  The FTIR instrument generates a molecular spectrum of the oil sample and the amount of additives can be detected by comparing the used oil sample with new oil or against a standard series made of the additives under investigation. Molecular analysis of lubricants and hydraulic fluids by FTIR spectroscopy generates direct information on molecular species of interest, including additives, fluid breakdown products, and external contamination. As FTIR spectroscopy is not relatively very expensive, it is used as a routine test, the result of which can be investigated or enhanced by some other tests whenever require. For instance, if FTIR indicates high oxidation the lab will then perform the TAN test to confirm. In today's machinery maintenance, it is a standard practice to have the FTIR signature of the virgin oil or lubricant to be able to detect the presence of abnormal compounds in the used oil and lubricant. In fact, a differential spectrum can be obtained by subtracting the spectrum of the new lubricant from that of the used lubricant to clearly reveal the area of change; thus, existence of a historical spectrum database of numerous virgin reference lubricants and oils is critical for accurate analysis [151], [286]. FTIR spectroscopy is particularly effective in measuring some specific factors which are listed in table 55, in the next page.

A FTIR Spectroscopy System

Figure 180 A FTIR spectrometer [WS105]

Table 55 Measureable factors by FTIR and their brief descriptions and explanations

Factor	Brief Description and Explanation
Fuel	Fuel dilution measurement indicates the relative amount of unburned fuel present in lubricant and is reported as percentage volume. Most engines are built to tolerate a certain amount of fuel dilution, but excessive amounts can lead to improper lubrication and thus accelerated wear. The presence of fuel indicates poor combustion due to incorrect fuel/air ratio that can be due to a clogged air filter, an ignition problem, by-passing injector pump elements, dribbling injectors, leaking lines, faulty transfer pumps, extended idling periods under no- or low-load conditions, or too low operating temperatures.
Soot	Soot measurement reveals the amount of insoluble soot carbon suspended in a lubricant or oil. Soot particles result from the incomplete combustion of fuel and, since they are too small to be removed by the filter, remain suspended in the oil. Soot builds up continuously until it reaches an unacceptable level. That level depends on the type of engine and lubricant. Diesel engines tolerate higher soot levels than gasoline engines. The rate of soot generation depends on engine design and type of fuel and operating conditions. A high soot value may indicate poor combustion due to incorrect fuel/air ratio, a clogged air filter, or over extended oil change period.
Ester	Ester breakdown may indicate the presence of water from condensation caused by low operating temperatures or from a coolant leak. In fact, synthetic lubrication oils usually contain a high proportion of synthetic poly-ol esters. These esters are susceptible to breakdown in the presence of water and acids (hydrolysis). Ester breakdown contributes to the acidity of the oil and can result in the formation of crystals of the base poly-ol, leading to clogging of filters.
Glycol	Glycol measurement indicates the presence of glycol or antifreeze contamination in the lubricant. Excessive glycol levels promotes lubricant breakdown leading to possible corrosion.
Water	Water content can change lubricant properties through reaction with the additives and emulsification. Water will also accelerate corrosion. The presence of free hydrogen from water may also cause localized micro embrittlement. The FTIR water measurement is only used for water between 0.1% and 1.0%. Higher or lower levels are measured using the Karl Fischer method for better accuracy.
Nitration	Nitration is a measure of the acidic buildup when nitrogen oxides are formed in harsh environments such as engine crankcases. Nitrogen oxides produced from the oxidation of atmospheric nitrogen during the combustion process react with the oil. Nitration increases the viscosity of the oil and is the major cause of the build-up of varnish or lacquer in engines. A high nitration value indicates incorrect fuel/air ratio, incorrect spark timing, excessive loads, low operating temperature, or piston ring blow-by.
Sulfation	Sulfation is a measure of the acidic buildup (sulfurous and sulfuric acid) due to sulfur compounds. This will cause oil degradation and create a very corrosive condition. Sulfur oxides are produced by the combustion of sulfur compounds present in fuel. These oxides react with water, also produced by the combustion process, to form sulfuric acid. The sulfuric acid is intended to be neutralized by the oil's basic additives, forming inorganic sulfates. A rapid increase in the sulfation value may indicate the use of a high sulfur content fuel, poor combustion, over-cooling, or the rapid depletion of anti-wear additives.
Oxidation	Oxidation is a measure of lubricant breakdown based on age and heat conditions. Oil exposed to oxygen from water and air at elevated temperatures will oxidize to a variety of compounds, the majority of which are carbonyl compounds, including carboxylic acids. Carboxylic acids contribute to the acidity of the oil, and thus, to corrosion. Oxidation will also increase the viscosity of oil by producing sludge and varnishes that are detrimental to the lubricant and equipment.

- *Total Chlorine Content Test:* Chlorine compounds are used as EP additives to prevent sliding metal surfaces from seizing under extreme pressure. These compounds react chemically with the metal to form an inorganic film to prevent the welding of opposing asperities, microscopic projections on metal surfaces that result from normal surface-finishing processes, and the consequent scoring which is distress marks or long, distinct scratches on sliding metallic surfaces in the direction of motion that is destructive to these metal surfaces under high loads. The result of the test is shown in parts per million or ppm.

Oil analysis can be entirely undertaken through:

- *Viscosity Test:* Viscosity is the single most important physical property of a lubricant and is directly related to the lubricant film strength (i.e. load carrying capacity). It is actually a measure of an internal shearing-resistant force of a lubricant, a factor in the formation of lubricating films under both thick and thin film conditions. Viscosity affects heat generation in bearings, cylinders, and gears; it governs the sealing effect of the oil and the rate of consumption or loss, and, it determines the ease with which machines may be started under cold conditions. Highly viscous lubricants do not flow as fluent as the ones with lower viscosity; however, they have a higher load capacity. It is central to use the proper lubricant with the correct viscosity in a given system. Equipment manufacturers must provide the information regarding the proper type and grade of lubricant that should be used in a given system. Periodic measuring of viscosity is done to ensure that the viscosity does not deviate significantly from the standard value. An abnormal viscosity value is an excellent indicator of a problem, although pinpointing the root cause can be complicated [286]. Viscosity test basically measure a lubricant's resistance to flow at a specific temperature. If viscosity of a lubricant in use varies too far from the baseline, corrective action may be required. The allowable range of a lubricant viscosity is typically defined as -15% to +15% from baseline. Fluid manufacturers usually list two baseline viscosity levels in the specifications for their lubricants, one at 40°C and another at 100°C. If a lubricant viscosity increases beyond its acceptable range, possible causes may be lubricant oxidation, foaming, emulsion with water, mixed lubricant condition, or solids contamination.

If a lubricant viscosity decreases beyond its acceptable range, possible causes could be molecular shearing, mixed lubricant condition or fuel/solvent contamination. This can happen under the courses of heat and pressure. Generally, a poor quality lubricant has a tendency to be molecularly sheared either easily or in a relatively short period of time [151], [647]. The changes in viscosity can also be reported via the viscosity index or VI, which is a measure of viscosity change of a lubricant within a given temperature range or, in other words, how a lubricant's viscosity varies with temperature. A low VI indicates a relatively large change in viscosity with temperature, whereas a high VI shows a relatively small change in viscosity with temperature. Usually a lubricant with high VI is better than the one with low VI, providing all other parameters are the same. VI is an important property in engine oils and should be monitored closely. It is usually called for VI when the machine is required to operate over a wide temperature range [132].

Viscometers

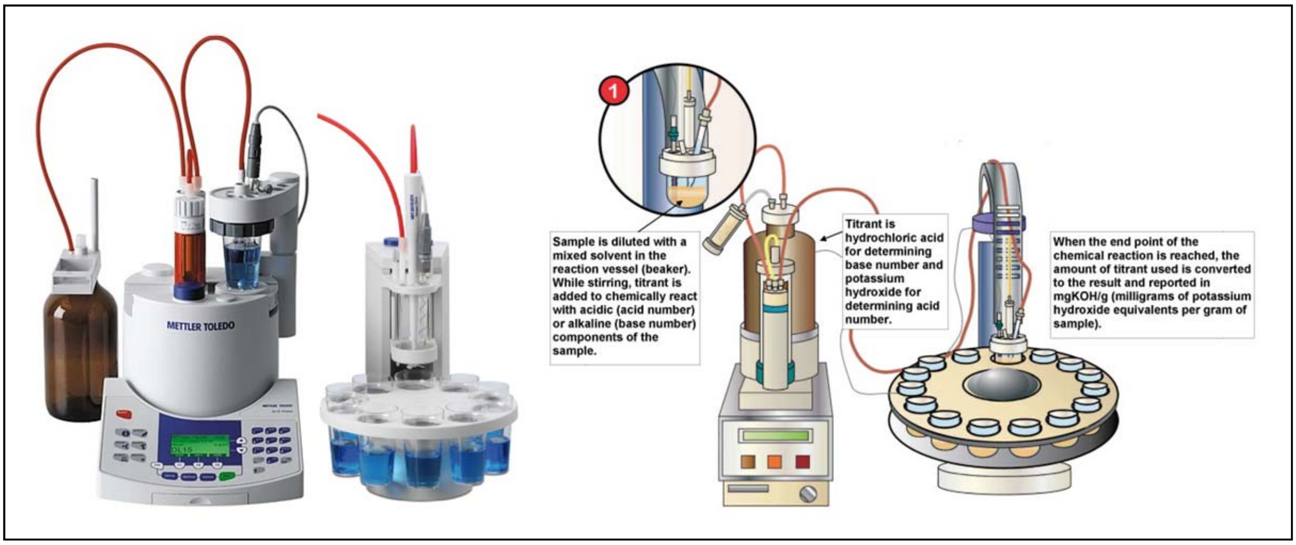
Figure 181 Photos of bench-type, handheld and in-line viscometers [WS22], [WS51]

- *Total Acid Number Test:* Organic acids, a by-product of oil oxidation, degrade oil properties and lead to corrosion of the internal components. Presence of acidity indicates the extent of oxidation of a lubricant and its ability to neutralize acids from exterior sources such as combustion gases. The acidity of lubricants is by titration and is expressed as the amount of milligrams potassium hydroxide required for neutralization (mg KOH/g); the resultant number is called the total acid number or TAN. In fact, the TAN is a measure of the amount of acid in the oil, but it is not an absolute value of the amount of acid present [445].

  The TAN test relies on the fact that as oil oxidizes, it forms carboxylic acids that increase the oil's acid number. By comparing the acid number of a used lubricant or oil sample with a new reference sample of the same oil, the degree of oxidation can be determined. As the oil or lubricant oxidizes the TAN increases compared to the unused one; however, the additives in most new oils contribute a certain TAN or acidity. Therefore, it is critical to determine and monitor changes from new oil reference. An increase in TAN may designate lube oxidation or contamination with an acidic product, but a lower TAN than the reference values usually indicates a lower level of required additives. It is crucial to underline that a severely degraded lubricant indicated by a high TAN may be very corrosive and quite damaging [151], [132].

- *Total Base Number Test:* Total base number (TBN) test measures of alkaline reserve within an oil or a lubricant sample. The alkaline reserve in the sample is measured by a precision titration method and is expressed as the amount of milligrams potassium hydroxide required for neutralization (mg KOH/g). This alkaline reserve is capable of neutralizing the acidic products. This test is usually performed on engine oil samples especially diesel engine oils. Indeed, new oil starts with the highest TBN it possesses. During the time the lubricant is in service, the TBN decreases as the alkaline additives neutralize acids. TBN is an essential element in the establishment of extended oil drain intervals since it indicates whether the additives are still capable of providing sufficient machinery (sp. engine) protection [151], [132].

A Titration System for TAN/TBN Testing



Sample is diluted with a mixed solvent in the reaction vessel (beaker). While stirring, titrant is added to chemically react with acidic (acid number) or alkaline (base number) components of the sample.

Titrant is hydrochloric acid for determining base number and potassium hydroxide for determining acid number.

When the end point of the chemical reaction is reached, the amount of titrant used is converted to the result and reported in mgKOH/g (milligrams of potassium hydroxide equivalents per gram of sample).

Figure 182 A photo and a schematic of a titration system used for TAN and TBN testing [WS4], [WS78]

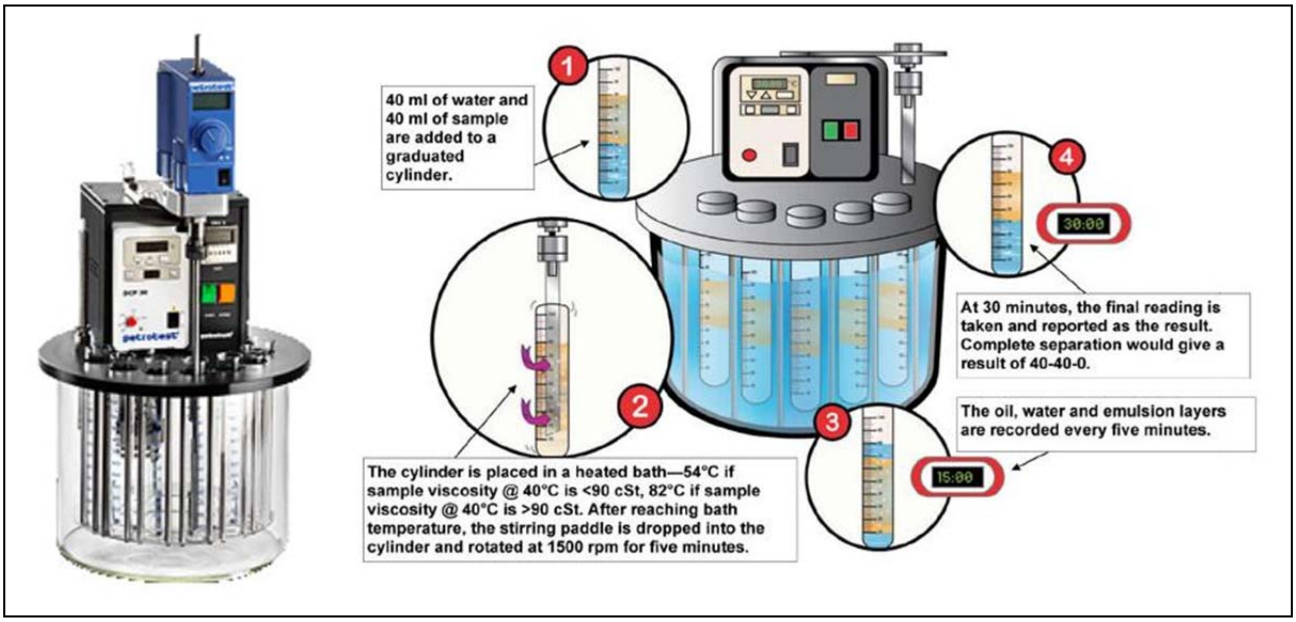
- *Bacteria, Fungi and Mold Test:* This test is particularly undertaken to inspect the condition of oil in the storage tanks by determining and measuring the existence and amount of bacteria, fungi and mold in the oil. Presence of these factors in oil storage tanks denotes the fact that the tanks have not been properly maintained. It is important to express that such a test detects only aerobic bacteria and will not be able to identify anaerobic bacteria.

- *Copper Strip Corrosion Test:* This test identifies the relative degree of corrosiveness to copper (due to active sulfur compounds) of different petroleum products such as fuels, solvents, greases and lubricating oils having a Reid vapor pressure no greater than 18 psi or 124 kPa. A polished copper strip is immersed in the sample at elevated temperature. After the test period, the strip is examined for evidence of corrosion and a classification number from 1-4 is assigned based on a comparison with the available copper strip corrosion Standards. Remarkably, this test only identifies copper corrosion but not ferrous metal corrosion.

- *Demulsibility Test:* It is well known that water is an undesirable contaminant in lubricants and functional fluids. Oil and water under certain conditions will form an emulsion, which can have adverse consequences. Water not only reduces the effectiveness of the lubricant or fluid, it tends to form deleterious by-products, particularly in relation to the metal parts in contact with or utilizing the lubricant or functional fluid. For instance, water present in a lubricant is responsible for the formation of objectionable mayonnaise-like sludge which in turn promotes the formation of hard-to-remove deposits from various parts of the machinery being lubricated. Apparently, the formation of the sludge is preceded by the water forming an emulsion with the lubricant oil. The ability of a lubricating oil to separate from water and resist emulsification is an important performance characteristic for applications involving water contamination and turbulence.

  Demulsibility test, which is also known as water separability test, is a method for measuring the ability of petroleum oils or synthetic fluids to separate from water at a specified temperature (54°C for most oils, but this may be increased to 82°C for oils with a viscosity above 90 mm^2 at 40°C). In other words, water separability test measures the ability for a lubricant to shed water and prevent an emulsion from forming. Water separability is determined by stirring equal volumes of water and sample together at this controlled temperature to form an emulsion and observing the time required for separation of the emulsion to occur. Poor water separability inhibits the proper performance of industrial lubricants. This test is suitable for petroleum oils and synthetic fluids.

Water Separability Testing



40 ml of water and 40 ml of sample are added to a graduated cylinder.

The cylinder is placed in a heated bath—54°C if sample viscosity @ 40°C is <90 cSt, 82°C if sample viscosity @ 40°C is >90 cSt. After reaching bath temperature, the stirring paddle is dropped into the cylinder and rotated at 1500 rpm for five minutes.

The oil, water and emulsion layers are recorded every five minutes.

At 30 minutes, the final reading is taken and reported as the result. Complete separation would give a result of 40-40-0.

Figure 183 A photo and a schematic of a system for water separability testing [WS76], [WS78]

- *Density or Specific Gravity Test:* Measurement of relative density or specific gravity (i.e. of the mass of a given volume of product and the mass of an equal volume of water, at the same temperature) can be used to confirm that the correct oil is in use by comparison of the result against product specification. The determination of density can be carried out using a digital density meter, and can also be used to calculate concentrations of one fluid in another (if the densities of both fluids are known). Specific gravity as a relative value (i.e. the density of a sample divided by the density of water at the same temperature) can be determined by a hydrometer. A hydrometer is an instrument with a glass graduated-float weighted with mercury or lead shot at one end (to make it float upward) which is dipped into the liquid sample and after a short equilibration time it swims at a certain level (i.e. when the mass of the hydrometer is equal to the buoyancy effect). The higher the density of the sample, the less the hydrometer will sink. The level of equilibration directly reads the specific gravity. Today, hydrometers are increasingly being replaced with modern digital density meters.

Density Meters

Figure 184 A lab-type and a handheld density meters [WS4]

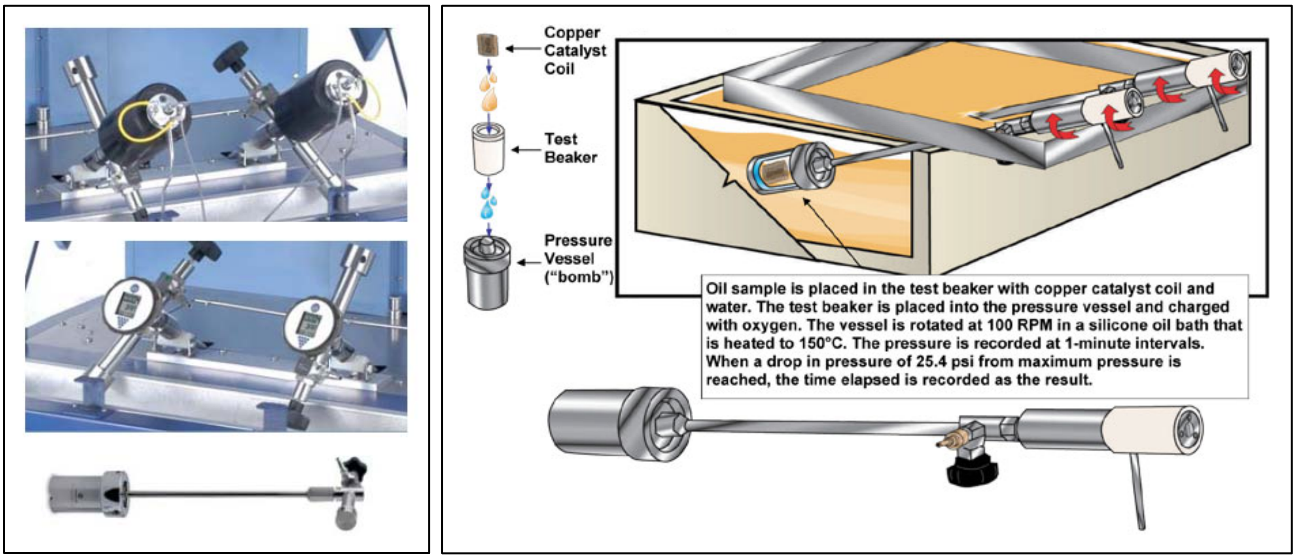
- *Foam Test:* A lubricant's propensity to foam can be identified by blowing air through a sample at a specified temperature and measuring the volume of foam that remains after a settling period. Foaming can result from disproportionate agitation, inappropriate fluid levels, air leaks, contamination or cavitation which is the pitting or wearing of a solid surface as a result of the collapse of a vapor bubble. Foaming can cause sluggish hydraulic operation, air binding in oil pumps and tank or sump overflow. The results are shown in milliliter (mL) of foam.

- *Four Ball Wear Test:* This test identifies a lubricant's antiwear properties under boundary lubrication (i.e. metal to metal contact). This technique is useful to evaluate friction and wear of liquid lubricants, or greases, in sliding contact. Its concept is that three steel balls are clamped together to form a cradle upon which a fourth ball rotates on a vertical axis. The balls are immersed in the oil sample at a specified speed, temperature and load. At the end of a specified test time, the average diameter of the wear scars on the three lower balls is measured. During the test, the load is increased every 10 minutes up to the point where the frictional trace indicates incipient seizure. The coefficient of friction is measured at the end of each 10 min interval. The test results are usually shown in kilogram force unit.

- *Rotary Pressure Vessel Oxidation Test:* RPVOT test, which was previously known and practiced as rotary bomb test, has been developed for the monitoring of in-service oils and lubricants to notify of a possible loss in oxidation resistance. As oxidation is driven by heat and exposure to contaminants like water, entrained air and catalytic metals, the oil sample, water and a copper catalyst coil are placed in a pressure vessel. The pressure vessel is then charged with oxygen, placed in a temperature-controlled bath and rotated. When a drop in pressure is achieved, the RPVOT result is the number of minutes it took to reach that drop. Standards identify that an RPVOT drop to 25% of the new oil RPVOT value with a concurrent increase in acid number as a warning limit. However, when the RPVOT is approximately 50% of the RPVOT of the oil when new, maintenance action should be initiated. The lower the RPVOT result, the higher the oil's potential is for developing sludge or varnish. Typically, the oil or lubricant that has reached its minimum allowable RPVOT values needs to be changed. The RPVOT test is considered to be very reliable, but it is time consuming, costly (approximately 150 € per sample) and requires a great deal of direct supervision. As a result, the RPVOT test is not suitable for a wide cross-section of lubricated machines in the plant. However, this test has proven its applicability for the periodic (e.g. annual, semiannual or quarterly) and infrequent assessment of large critical systems such as large industrial gearboxes and engines, compressors, turbines and their generators [21], [299], [431], [567].

  In fact, testing turbine oils is an effective means for monitoring wear and contamination, but large sump capacities and shutdown implications in many turbine applications make oil changes expensive and difficult. Evaluating the oil's oxidative stability is an effective way to determine its remaining useful life and the safest, most cost effective way to know whether the oil change is crucial or not. As turbine oil degrades, it forms weak organic acids and insoluble oxidation products that adhere to governor parts, bearing surfaces and lube oil coolers. After a period of time, these oxidation by-products and carbon insolubles cure on surfaces causing a significant change in critical clearances, and in some instances prevent the oil from providing adequate cooling to the bearings and fouling turbine control elements and heat exchangers.

Rotating Pressure Vessel Oxidation Testing



Oil sample is placed in the test beaker with copper catalyst coil and water. The test beaker is placed into the pressure vessel and charged with oxygen. The vessel is rotated at 100 RPM in a silicone oil bath that is heated to 150°C. The pressure is recorded at 1-minute intervals. When a drop in pressure of 25.4 psi from maximum pressure is reached, the time elapsed is recorded as the result.

Figure 185 A photos and a conceptual schematic of RPVOT systems [WS91], [WS78]

Wear analysis can be entirely undertaken through:

- *Wear Debris Analysis:* In the event of high wear debris levels wear debris analysis may be called for. Indeed, wear debris analysis is a technique for nonintrusive examination of the oil-wetted parts of a machine. Parts of a machine which move relative to each other tend to generate wear debris from their interactions, particularly if their operation is not entirely smooth and well lubricated or if the surfaces are highly stressed and therefore prone to local fatigue or pitting. In this process, a fixed volume of homogenized oil sample is filtered through a membrane filter. This filter membrane is then observed under an optical microscope to determine the sizes, types, and density of the wear and contaminant particles. As the wear of load carrying lubricated surfaces is usually a slow progressive process, wear debris analysis allows the assessment of surface deterioration. By observing the quantity and nature of wear debris, it is possible to assess the wear and condition of various machine components which are lubricant washed. Wear debris analysis is critical when particles larger than 10 microns are predominant in the system. As mentioned, the analysis provides indications of: type of particles, size of particles, shape of particles, type of damage, and number of particles [132], [246], [542].

- *Analytical Ferrography:* Scott et al. define ferrography as a method of recovering particles from a fluid and depositing them on a substrate according to size and magnetic susceptibility for analysis [542]. In fact, ferrography is a technique that provides microscopic examination and analysis of wear particles separated from all types of fluids. Developed in the mid 1970's as a predictive maintenance technique, it was first used to magnetically precipitate ferrous wear particles from lubricating oils; then after, there were different methods developed to precipitate nonmagnetic particles from lubricants and oils and quantifying wear particles on a glass substrate which is called ferrogram. Analytical ferrography allows analyst to visually examine wear particles present in a sample. The analytical ferrograph is used to prepare a ferrogram of wear particles for microscopic assessment and photographic documentation. The ferrogram is an important predictive tool, since it provides an identification of the characteristic wear pattern of specific pieces of equipment. After the particles have deposited on the ferrogram, a wash is used to flush away the oil residue or water-based lubricant. After the wash fluid evaporates, wear particles remain permanently attached to the glass substrate and are ready for microscopic examination. Analytical ferrography provides comprehensive information about a lubricant or oil sample. Nonetheless, a trained analyst is needed to visually determine the type and severity of wear deposited onto the substrate by using the high magnification microscope and to identify and classify the wear particles according to size, shape, and metallurgy [151], [460].

A Ferrogram Maker

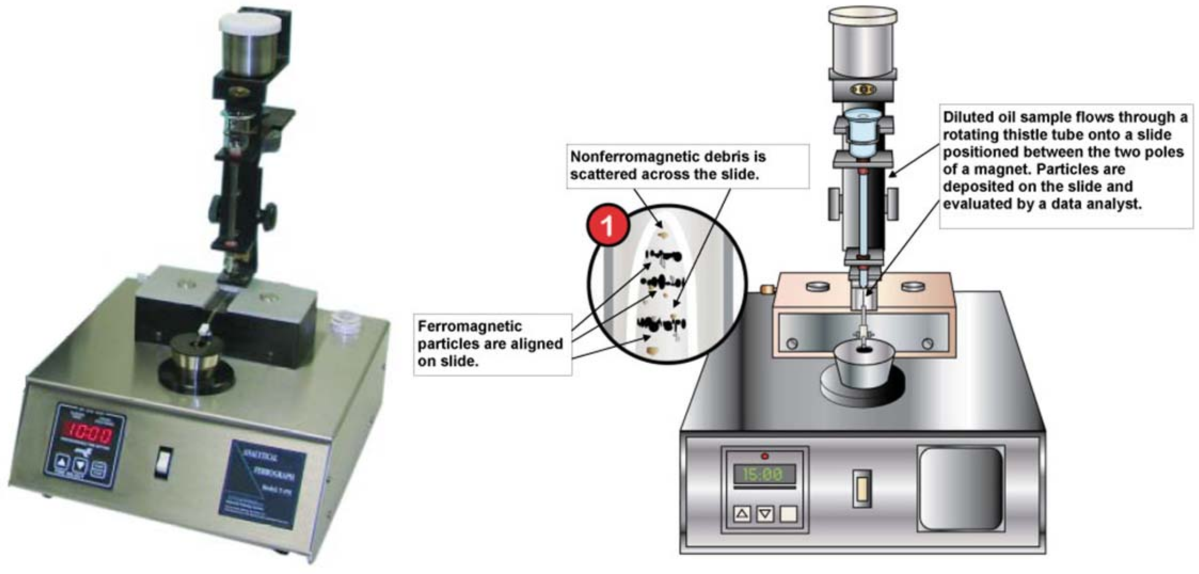


Figure 186 A picture representing a photo and a schematic of a ferrogram maker [WS89][WS78]

- *Direct Read Ferrography:* This method is used to determine the amount and size distribution of wear particles in a lubricant or oil sample. It employs a direct read ferrograph monitor, which quantitatively measures the relative amount of ferrous wear in a lubricant or hydraulic oil. This is a trending tool that permits condition monitoring through examination of fluid samples on a scheduled, periodic basis that reveals changes in the wear mode of the system. A compact, portable instrument that is easily operated even by a non-technical personnel. The involved technique is so that the instrument precipitates particles onto the bottom of a glass tube that is subjected to a strong magnetic field. Fiber optic bundles direct light through the glass tube at two locations where large and small particles are deposited by the permanent magnet. At the onset of the test, before particles begin to precipitate the instrument is automatically zeroed with a microprocessor chip as the light passes through the oil to adjust for its opacity. The light is reduced in relation to the number of particles deposited in the glass tube, and this reduction is monitored and displayed on a LCD panel. Two sets of readings are obtained: one for direct large (DL) denoting the particle sizes greater than 5 microns and one for direct small (DS) referring the particle sizes less than 5 microns.

  Afterwards, wear particle concentration (WPC) is derived by adding DL + DS divided by the volume of sample, establishing a machine wear trend baseline. Machines starting service go through a wearing in process, during which the quantity of large particles quickly increases and then settles to an equilibrium concentration during normal running conditions. Machines wearing abnormally will produce unusually large amounts of wear particles indicating excessive wear condition by the direct read ferrograph in WPC readings. If WPC readings are beyond the normal trend a Ferrogram sample slide is made with the fluid for examination by optical microscopy [529].

A DR Ferrograph

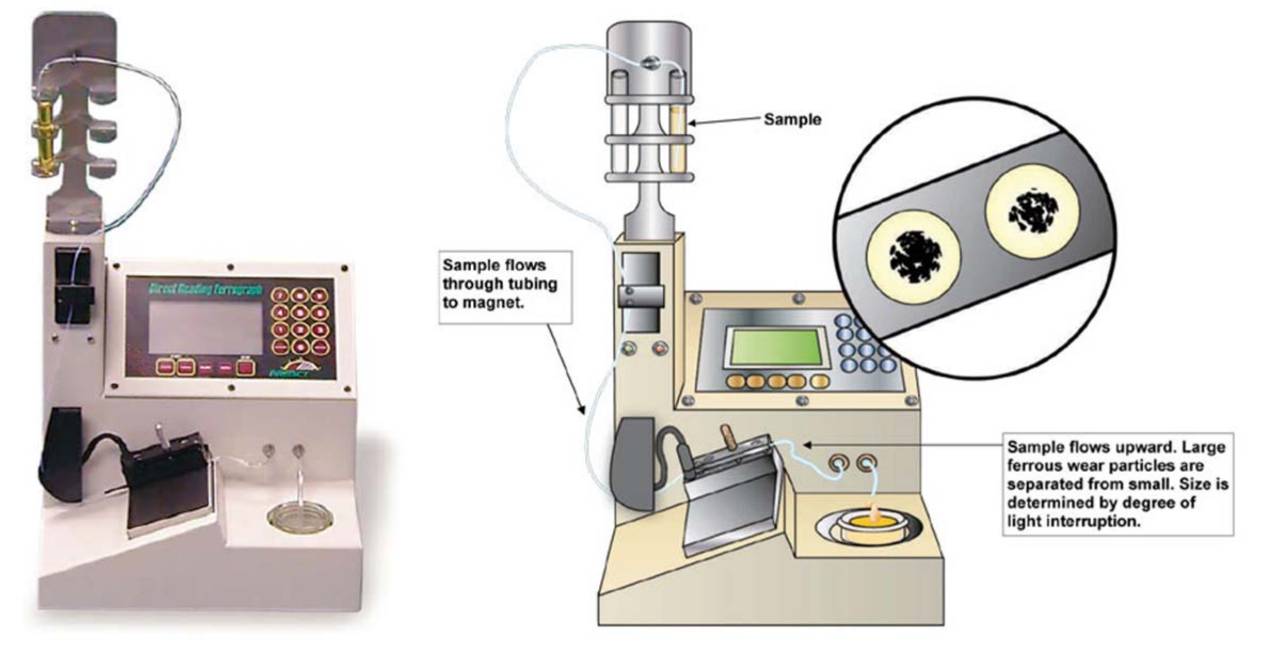


Figure 187 A photo and a schematic of a direct read ferrograph [WS80], [WS78]

- *Millipore Patch Test:* This test, which is also known as micro patch, is usually undertaken when another test such as Rotrode Filter Spectroscopy (RFS) shows that primarily nonferrous metals are involved with a severe wear mode, i.e., the presence of high levels of coarse, nonferrous metals. The test allows the particles of interest to be explored under a high-powered microscope in order to identify the size, shape, metallurgy, and surface texture of the particles. This facilitates evaluating wear condition in the machine and the source of the severe wear particles. Patch test should only be performed on an exception basis because it is quite time consuming and expensive. Recent technology combines traditional spectroscopy with RFS to quickly identify all the metals (both fine and coarse) in the oil or lubricant sample; this eases the decision making whether to perform a patch test or not [647]. This test is ideal for system cleanliness investigation and verification.

- *Ferroscopic Testing:* In this testing method ferrograms are typically examined under a microscope that combines the features of biological and metallurgical microscopes. Such equipment utilizes both reflected and transmitted light sources, which may be used simultaneously. Green, red, and polarized filters are also used to distinguish the size, composition, shape and texture of both metallic and nonmetallic particles, which is a key component to proper diagnosis. Notably, particles generated by different wear mechanisms have characteristics which can be identified with the specific wear mode. Rubbing or adhesive wear particles found in the lubricant of most machines have the form of platelets and are indicative of normal permissible wear; cutting or abrasive wear particles take the form of miniature spirals and loops. An accumulation of such particles is indicative of an abrasive wear process. Particles consisting of compounds can result from an oxidizing or corrosive environment; steel spherical particles are a characteristic feature associated with crack propagation in rolling contacts.

  Specific regimes of wear can be identified by the nature of the particles produced by surfaces in sliding contact. Scott declares that different mechanisms such as rolling bearings, gears and sliding bearings produce distinctive particles [542]. An atlas of such particles is available and this is also extended to cover characteristic nonmetallic and nonferrous particles. Energy dispersive x-ray analysis in the scanning electron microscope of particles on a ferrogram can establish their composition and allow postulation of their source. Controlled heating of ferrograms to oxidize the particles can provide qualitative identification by differential oxidation rates of different metals and alloys and consequently different color changes according to oxide thickness [529].

A Microscope Used for Ferroscopic Testing

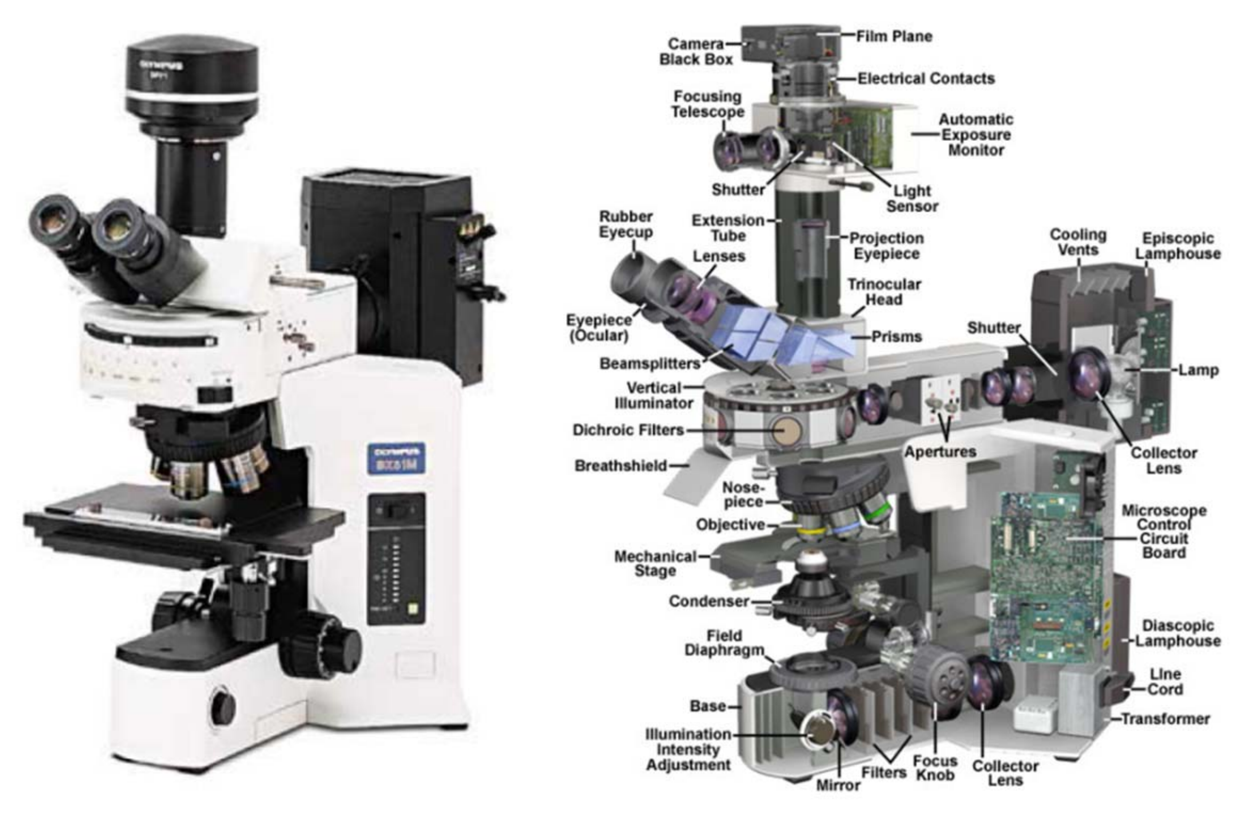


Figure 188 An Olympus BX51, a microscope with transmitted and reflected light for Ferroscopic testing [WS70]

- *Rotrode Filter Spectroscopy:* This technique, which is abbreviated as RFS, monitors fine coarse metals and contaminants, and ousts the results in part per million (ppm). RFS is useful in early detection of abnormal wear. Indeed, the atomic emission spectrometer used in this technique only identifies dissolved metals and the finest debris which are usually associated with benign or normal wear. However, coarse particles are of greater interest as they are generally bred by severe wear modes. Such a limitation is overcome by pre-filtering the sample through one of the electrodes, called a rotrode or rotary disk electrode (RDE). The rotrode is a porous carbon disc, and that characteristic makes it an ideal filter.

A fixture has been designed for use outside of the spectrometer to clamp the disc so that the oil sample can be drawn through the outer circumference of the disc when a vacuum is applied to the inside hub. The particles in the oil are captured by the surface of the rotrode, forming a thin line around the outside edge of the disc. Residual oil is washed away with solvent, the disc is allowed to dry, and the particles remain adhered to the rim of the rotrode in the right position to be vaporized when the rotrode is zapped in the spectrometer. This provides an excellent level of sensitivity. RFS is fast and economical, making it an ideal screening test in conjunction with both analytical ferrography and patch test [647]. Remarkably, RFS instruments do not inevitably require any sample pretreatment and the measurements are relatively cheap to carry out. However, one intricacy with RFS is the strong effect of changes in instrumental factors on the test results [319], [569], [619].

An RFS system such as shown below has a five-station fixture of funnels. The electrode clamp assembly with a fresh carbon disc is installed in one of the RFS sample funnels. An oil sample is poured into the funnel and the funnel is clamped shut. With the start of the automated process, a vacuum/pressure pump pulls and pushes the sample through the RDE and the filtration process concentrates large wear particles on the surface of the electrode. A sensor determines when most of the sample has been filtered through the electrode and automatically starts the electrode cleaning and drying process. The RFS preparation process is complete when all the oil has passed through the disc electrode, residual oil has been washed away, and the electrode is dried. The operator then removes the electrode clamp assembly and uses it as a tool to install the electrode in a spectrometer for further analysis.

A Rotrode Filter Spectroscope

Figure 189 A picture representing a photo of an automated rotrode filter spectroscopy system [WS89]

- *Atomic Absorption Spectroscopy:* The atomic absorption spectrophotometer operates on the principle that atoms absorb only light of their own wavelength. A lubricant sample is vaporized in a flame and each element required is determined separately using a source lamp which limits light of the wavelength characteristic of the element. Light is absorbed on passage through the flame and comparison with a reference beam allows a direct measurement of element concentration. Standards of known element concentration are used for calibration [446], [569]. Atomic absorption spectroscopy (AAS) or flame atomic absorption spectroscopy (FAAS), and indeed, most of the spectroscopic requires the oils sample to be first nebulized into an excitation source, which atomizes and often also ionizes the elements of the sample. There are several pretreatment methods which are used when determining metals in oils using the spectroscopic techniques. A common way is to use organic solvents to dissolve and dilute oil samples and to nebulize the oil-solvent mixture as such to be used in the atomizer unit of the spectrometer. Methylisobutylketone (MIBK), diisobutylketone (DIBK), alcohols, xylene and naphtolite have been more commonly used with AAS technique. Dilution with organic solvents is a very fast pretreatment method and as such very suitable for quick check-ups of metal concentrations [319]. It is extremely useful when metal atoms are attached to organic molecules, like in many additive substances or in metal soaps, or when the solid metal particles are mainly small in size.

Atomic Absorption Spectrums of Iron and Aluminum

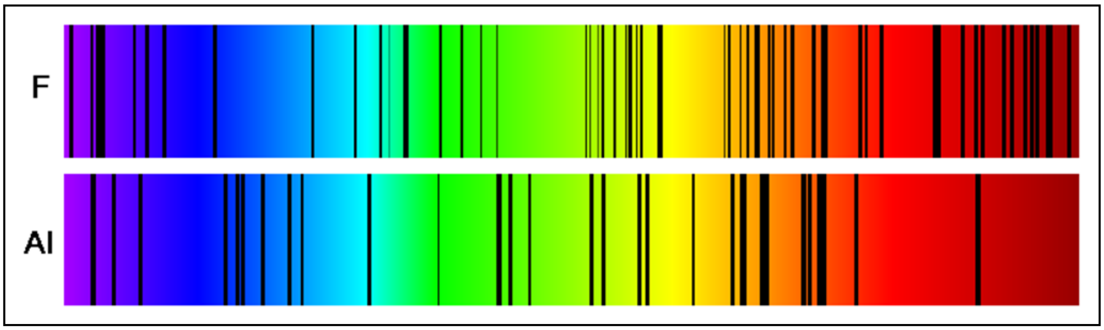


Figure 190 Atomic absorption spectrums of the elements iron and aluminum [WS1]

The obvious drawback of the dilution method is that organic solvents do not dissolve large solid particles. These particles will not be atomized perfectly in absorption or emission spectrometric methods [303]. Among the spectroscopic techniques, AAS is relatively inexpensive to purchase and use, plus, its routine operation is quite simple. However, sample consumption of the AAS instruments is high, its linear determination range is narrow, determining of refractory elements is difficult and chemical interferences are possible. Only one element at a time can be identified, resolved and verified with an AAS instrument [636].

An Atomic Absorption Spectrometer

Figure 191 A picture showing a photo of an AAS system [WS75]

- *Atomic Emission Spectroscopy:* This technique, which can be abbreviated as AES, monitors and quantifies the concentration of fine wear metals, contaminants and additives, and ousts the results in dissolved and fine particles ppm [636]. This is done via an atomic emission spectrometer that measures the characteristic wavelength of light emitted when elements are excited by an electrical discharge. Usually a small quantity of lubricant picked up on the periphery of a rotating graphite disc is vaporized in an electrical discharge to promote the emission of spectra by the metallic elements present. Photomultipliers aligned to spectral lines of interest are used to measure element concentration simultaneously in parts per million [542].

Atomic Emission Spectrums of Iron and Aluminum

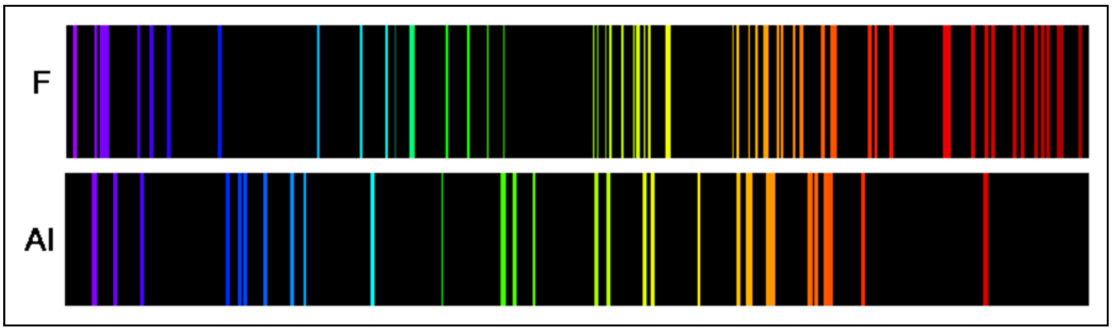


Figure 192 Atomic emission spectrums of the elements iron and aluminum [WS1]

Such a technique provides information on elemental concentration only, with no indication of the number or size distribution of wear particles. As particles measured by the spectrometer are normally less than 10 microns in size, then, a disadvantage of the technique is being blind to large particles which can be most dangerous in precision machinery [303]. AES is a technique that is most commonly used for trending concentrations of wear metals such as iron, lead, tin and copper. As stated before, AES also detects certain contamination; for example, coolant contamination can be detected by monitoring the concentrations of elements such as sodium and boron and dirt contamination can be detected by monitoring the concentration of silicon or occasionally aluminum. In general, the elements measured and monitored through this technique include: iron, chromium, nickel, aluminum, copper, tin, silver, lead, silicon, sodium, boron, magnesium, calcium, barium, zinc, phosphorus, molybdenum, lithium, titanium and vanadium [94], [315].

An Atomic Emission Spectrometer

Figure 193 A photo of an AES system [WS57]

- *Inductively Coupled Plasma Spectroscopy:* This technique, known as ICP spectroscopy, is an analytical technique used for the detection of metals as wear particles in fluids. It is a type of emission spectroscopy that uses the inductively coupled plasma to produce excited atoms and ions that emit electromagnetic radiation at wavelengths characteristic of a particular element. The intensity of this emission designates the concentration of the element within the sample [302]. An accepted pretreatment method employed with ICP is to use micro-emulsions, which incorporates mixing the oil with water and surfactants. The drawbacks of this pretreatment method are problems encountered with the stability of the emulsion, difficult preparation of standards and the same problem with the nebulization/atomization efficiency of large solid particles as with the use of organic solvents. On the other hand, it should be noted that adding acid to emulsified samples will dissolve the solid metal particles and improve the accuracy of the determination [228], [451], [608].

An Inductively Coupled Plasma Spectrometer

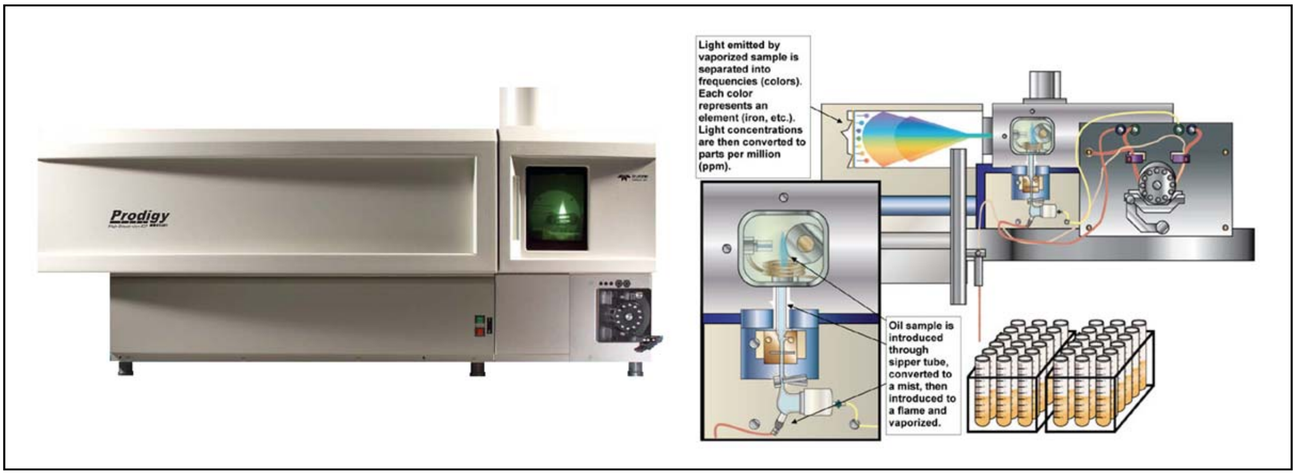


Figure 194 A photo and a schematic of an ICP Spectrometer [WS58], [WS78]

It is notable that ICP employed along with optical emission spectroscopic instruments offer a possibility to simultaneously measure almost all metals and some nonmetals. These instruments integrate methods which are almost free of chemical and possible spectral interferences with careful planning of the measurement [636]. However, the drawbacks of ICP are higher equipment expenses (i.e. purchase, maintenance and use) than RFS or AAS, plus high expertise, which is often required. It is essential to underline that the detection limits of both AAS and AES techniques are quite adequate for condition monitoring applications, but if better detection limits are requisite, mass spectrometry equipment enhanced with inductively coupled plasma can be employed; though, this is very expensive to purchase and use, and matrix effects in the form of several molecular ions formed in the plasma can be difficult to be removed [73], [184], [319].

- *Mass Spectrometry:* Mass spectrometry (MS) is based on slightly diverse principles to the other spectroscopic methods. The physics behind mass spectrometry is that a charged particle passing through a magnetic field is deflected along a circular path on a radius that is proportional to the mass to charge ratio, i.e. m/e. In an electron impact mass spectrometer, a high energy beam of electrons is used to displace an electron from the organic molecule to form a radical cation known as the molecular ion. If the molecular ion is too unstable then it can fragment to give other smaller ions. The collection of ions is then focused into a beam and accelerated into the magnetic field and deflected along circular paths according to the masses of the ions. By adjusting the magnetic field, the ions can be focused on the detector and recorded. Mass spectrometers are capable of separating and detecting individual ions even those that only differ by a single atomic mass unit so that molecules containing different isotopes can be distinguished [109].

Concept of Mass Spectroscopy

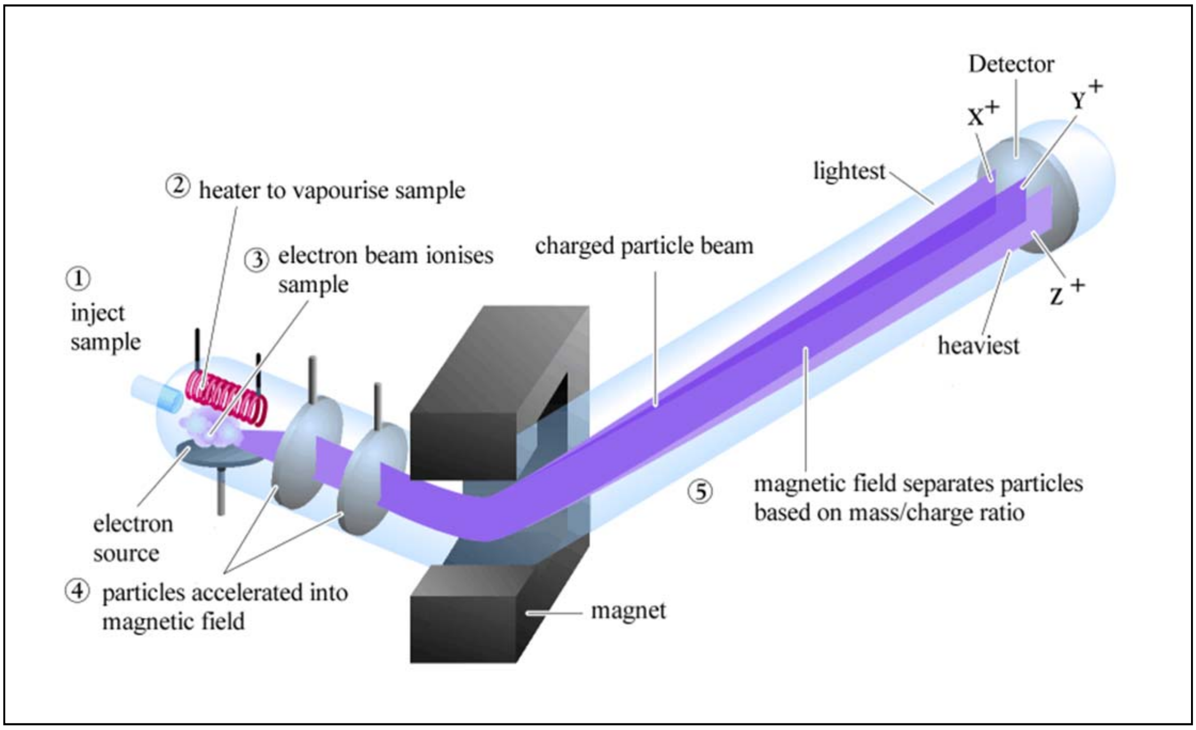


Figure 195 Concept of the physics behind mass spectroscopy and the common process along the tubular path in every mass spectrometer [109]

In fact, with the purpose of measuring the characteristics of individual molecules, a mass spectrometer converts them to ions so that they can be moved about and manipulated by external electric and magnetic fields. The three essential functions of a mass spectrometer, and the associated components, are: A small sample of compound is ionized, usually to cations by loss of an electron, the ions are sorted and separated according to their mass and charge, and the separated ions are then detected and tallied, and the results are displayed on a chart. Because ions are very reactive and short-lived, their formation and manipulation must be conducted in a vacuum. Atmospheric pressure is around 760 torr (i.e. mm of mercury). The pressure under which ions may be handled is roughly 10^{-5} to 10^{-8} torr (i.e. less than a billionth of an atmosphere) [106].

Although, each of the mentioned three tasks may be accomplished in different ways; however, in one common procedure, ionization is effected by a high energy beam of electrons, and ion separation is achieved by accelerating and focusing the ions in a beam, which is then bent by an external magnetic field. The ions are then detected electronically and the resulting information is stored and analyzed in a computer. Probably the most valuable information one is able to obtain from a MS spectrum is the molecular weight of the sample. Besides, MS stand alone or in combination with chromatographic methods can be an effective tool in the analysis of base oils and additives. For instance, MS along with chromatography has been utilized in determining antioxidants, metal passivators, lubricity improvers or anti wear agents in lubricating oils [52], [513].

- *Optical Emission Spectroscopy:* In this technique, which is known as OES, the metal atoms and/or ions are excited with the thermal energy of the excitation source. When the excitation state dies, and element-specific emission spectrum is produced. With the selection and isolation of a certain emission line, the concentration of the metal can be determined [569]. OES like other spectroscopic techniques like AAS and ISP requires the oils sample to be first nebulized into an excitation source, which atomizes and often also ionizes the elements of the sample. Plus it needs the pretreatment to determine metals in the oil samples. Like other spectroscopic techniques, a common way is to employ organic solvents and, xylene and kerosene are the frequently used solvents [319].

An Optical Emission Spectrometer

Figure 196 A photo of an OES system [WS89]

- *X-Ray Fluorescence Spectrometry:* This technique that is widely known as XRF employs an instrument in which each atom emits radiation in the x-ray region after stimulation. The detection system can measure the amount of metal atoms in the sample by determining the amount of x-ray energy generated by the atoms at their characteristic wavelengths [381]. XRF is a well-recognized method for quantitative elemental analysis of solids and liquids. Rather than employing electrons to stimulate the sample characteristic x-rays, it applies an x-ray beam via which the resulting spectrum is emitted immediately by the sample being called as fluorescence. As applied to wear debris samples composed of groups of particles, XRF provides wear rate and wear source information based on the composition of the entire debris sample. XRF has already proven the capability of providing a tangible failure alert over 100 hours in advance [659]. XRF, being a mass sensitive technique, does not have particle size cutoffs, and can be used to measure particles of any size. While there does exist a well-known particle size effect for XRF being concerned with efficiency and the details of quantification [141]. The sensitivity of XRF (i.e. x-ray counts per gram) is highest for small particles which are under 1 micron. The sensitivity of XRF to larger particles is less than for the small particles. That is, XRF benefits from high sensitivity from small particles which likely are present in smaller total mass. It can be concluded that XRF measures both small and large particles. Cumming and McDonald have found particle size to have only a minority effect on the XRF analysis of wear particles in real and modeled oil samples [147]. XRF has been observed to be up to fifty times more sensitive than AES for real samples containing large particles. Energy dispersive XRF (EDXRF) instrumentation is robust, not sensitive to alignment, and offers the ability to measure multiple elements simultaneously with a single, readily calibrated energy dispersive detector [656]. Although XRF cannot perform the required analyses for light elements such as Mg, Al, and Si while the particulates remain suspended in oil, this drawback can be eliminated by particular filtration.

To gain the highest sensitivities and access the widest range of atomic numbers, it is advisable to remove the particulates from the oil and perform the analysis in vacuum. Since particles thicker than -1 μn undergo significant x-ray absorption, samples of separated particles should be prepared as a single layer. The XRF technique has been used effectively to identify additive and wear metals in oil samples in addition to wear metals in lubricant filters. It has also been utilized for wear debris still suspended in the oil sample in addition to debris separated from the oil sample. Quantitative comparisons of the elemental analysis of actual wear particulates, performed by XRF and by wet chemical methods independent of particle size, have verified the accuracy of XRF for measuring samples composed of real wear part and dates, while highlighting deficiencies in other analytical methods in wide use. XRF has successfully performed the trending of wear rates, identification of wear chemical elements in the wear particles, and location of wear sources [656]. Besides, x-ray related technologies can also be utilized to analyze nonmetallic particles in oils by means of x-ray diffraction [194]. Nevertheless, it is notable that light metals such as magnesium and aluminum cannot be analyzed with XRF, and similar to ICP technique some matrix effects can be difficult to be removed [488], [674].

An X-Ray Fluorescence Spectrometer

Figure 197 A photo of an XRF spectrometer system [WS72]

Precise results of any tribological testing necessitate proper, reliable and accurate sampling. To attain full predictive advantage from the information that a tribological testing provides, the oil or lubricant sample must meet four major criteria. First, it must be representative of the oil in contact with the lubricated surface for the application being monitored. Second, it must be obtained at the appropriate sampling interval. Third, it must be analyzed, and reported in a timely manner in order to precisely reflect the current conditions in the application. Fourth, it must be properly annotated in order to clearly identify and reference the application. Consistently meeting these four criteria will lead to an effective sampling program.

In general, sampling should be performed during operation, or immediately after shutdown if that is the only option to insure that dirt and wear particles present in the fluid have not settled out, and that water or coolant contamination has not separated from the oil. This is important to ensure that the sample is representative of the actual conditions during operation and not artificial conditions caused by settling and separation that often occur during non-operating periods. Prior to sampling, the area around the sampling opening or sampling valve should be wiped clean so that surface dirt or dust will not accidentally fall into the sample container or the sample stream. This is particularly important if the sample is to be analyzed for wear metals or particle count. Additionally, samples should be taken from an active, low-pressure line, ahead of any filtration devices. For consistent results and accurate trending, samples should be taken from the same place in the system each time using a permanently installed valve. In order to monitor a specific component the valves should be located in a line just after and before the component. These locations are chosen because a sample extracted here will indicate if the component is starting to wear and requires to be replaced. On the other hand, if the whole system is to be monitored, the valve should be located in a main line. This is due to the fact that the oil which has passed all the components in the system also passes through this line; hence, an oil sample courier of the whole system can be attained.

Another crucial factor in oil sampling is the influence of flow characteristics. As Eleftherakis declares the most delegate sample is acquired from a location representative of the condition of the system and where the fluid flow is turbulent [179]. A turbulent flow is characterized by an irregular motion and macroscopic mixing motion perpendicular to the direction of the flow [350]. Turbulent flow often occurs at discontinuities, for example after a bend in a pipe. The opposite of turbulent flow is laminar flow, which is characterized by the fluid moving in parallel layers or laminas with no macroscopic mixing motion across them. The first choice in oil sampling is locations with turbulent fluid flow in a channel.

Examples of such locations for horizontal and vertical flows are shown in the below figure. However, if sampling from a laminar flow is compelled, then the sample is better to be taken from below in a horizontal line or from a downward flow in a vertical line. In case of a horizontal line, although sampling from below has the risk of getting settled particles into the sample but this can be overcome with extensive flushing to clean the valve. Indeed, such a location is a good choice if the monitored component is expected to give dense debris (e.g. pitting damage or abnormal wear). In case of a vertical line, the heavy particles are positioned relatively near the wall so by mounting a sampling tap on the wall of the pipe there is a better chance of getting a representative sample [63].

Location of Sample Taps in Turbulent Flow Channels

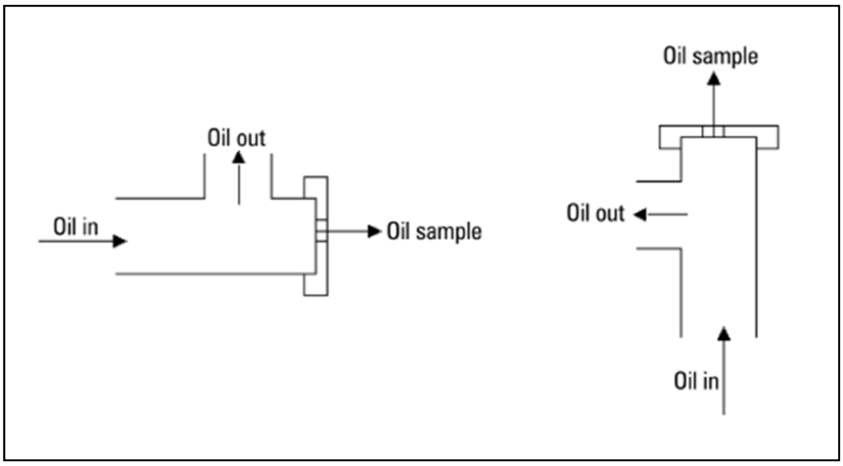


Figure 198 Proper location of oil sampling taps in horizontal and vertical channels with turbulent fluid flow [63]

Besides the location of sampling taps, flushing of sampling taps is of great importance too. In actual fact, the first oil sample extracted from the tap is not representative as usually the sediments are being flushed with the oil. For the problem to be solved the sampling point should be flushed. The volume that has to be flushed out depends on the contamination degree in the system and the amount available for flushing, since the system can have a limited volume of oil. ISO 4021 standard from the year 1977 recommends that a volume of 0.2 liter should be flushed out before a sample is taken, although this amount seems to be too little for most systems. There are other studies about the flushing time required for proper sampling. For instance, Rinkinen and Kiso in the year 1993 used a portable particle counter in field to research sampling on 28 hydraulic and nine lubrication systems. The flushing time for measurement couplings was based on 334 field measurements during the research project. It has been shown that after 4 minutes 50% of the measurement couplings become clean, but in case of a 90% requirement, 15 minutes of flushing is needed.

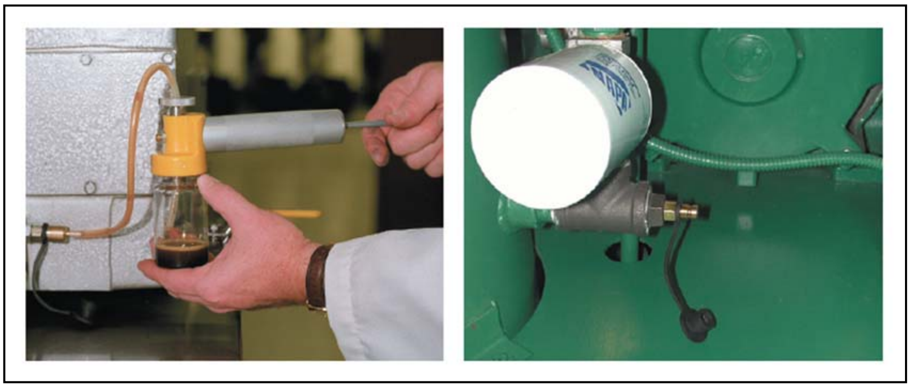
Sometimes it is need the sample oil from containers, especially for oil analysis purposes. In this case, possibilities of mistaking and errors increases so more safety measures have to be taken into account. Before taking a sample from an oil container, it is essential to thoroughly mix the oil in that container. If the oil is well mixed, the contaminants are also well mixed, but as soon as the mixing stops the sedimentation of particles starts. The factors preventing the particles sediment are the flow in the container and that particles have different shapes which make them sediment faster or slower or indeed the duration of sampling. For example, in case of a small container such as a gearbox, particles of 100 µm in diameter and above are almost impossible to be caught if one does not take the sample in five minutes. The seminal elements in successful sampling are where the sample is taken and if the sample can be extracted in time before the particles settle at the bottom of the container [63].

It is central to highlight that the least desirable place to obtain a sample is through the drain plug of a container since this is the point engineered to capture contaminants and contain sludge buildup. However, if this is the only place available to take a sample, it is needed to flush out of the drain port before collecting the sample as this will help reducing the sludge that often gathered on the bottom of the containers from contaminating the sample. To verify the condition of a system containing oil or lubricant, a sample of the system's oil must be extracted and by analysis of which data about its particles (e.g. size, quantity and shape, and the type of contamination) can be retrieved. The sampling can be carried out dynamically, when the fluid is in motion while the machine is operating, or while the fluid is static. Dynamic sampling is generally preferred to static sampling as it increases the possibility of extracting a proper representative sample because the turbulence prevents sedimentation and induces mixing of the particles. There are three main different types of sampling techniques, in-line and on-line techniques which are indeed continuous sampling, monitoring and analyzing, and off-line technique which is actually laboratory-scale sampling and analysis [63], [179], [196], [198], [287], [619], [677]:

- *In-line sampling* that is continuous monitoring within the system has different advantages such as the taken oil sample is the representative of the whole batch and the environmental errors connected to bottle sampling is minimized. However, because of the high flow rates in most systems, in-line monitoring is often impossible or performed with qualitative techniques. In-line instruments are often electrical sensing instruments or instruments using ultrasound radioactive analyzing methods. Though, the detectability of these instruments is still under question since the instruments often interfere with the flow when undertaking the measurements. This interference changes the flow pattern and thus the particle distribution in the line. Hence, the in-line techniques available today are not really usable to attain absolute measurement values out in the field.

- *On-line sampling* that is continuous monitoring parallel to the system has a compromised role between off-line and in-line sampling. In this case, the instruments are attached to the system using a by-pass line. Examples of instruments that employed for on-line sampling are automatic particle counters, mesh blockage instruments, magnetic detectors, inductance instruments, electrical conductance instruments, and instruments using radioactive methods. The on-line and in-line techniques are sometimes not adaptable to the system for different reasons such as difficulty in reaching the sampling point or vibrations while the system is running, as is the case of a gearbox. On-line instruments today can often be used to take bottle samples using a built-in vacuum pump. In-line instruments are not capable of taking samples from the flow. The advantages of on-line sampling over off-line sampling techniques are that direct results are obtained, bottle cleaning is not necessary, less technical expertise is necessary, and there is less risk of errors when withdrawing a sample. The main disadvantage of on-line sampling is that it does not provide information about particle material or how the particles have been generated. Fluids containing air or water, precipitation, dark oils, viscous oils or excessively contaminated oil are known to be problematic when sampling on-line.

- *Off-line sampling* is mainly performed with bottle samples withdrawn from the system and is adaptable to most of the systems and is therefore a widely used method. The main advantage of this technique is that the oil sample can be kept for further analysis. This is necessary if more information about the particles in the system is needed. The downside of the off-line sampling method is that the possibility of errors is much greater than in the other techniques. For example, if the bottle is open for a longer time after or while the sample is taken, contamination from the air can interfere. Other problems are dirt remaining in the bottle after cleaning and chemical changes in the oil during transportation, when sending the bottle for analysis. Because of the risk of errors using this technique, the sampling is of the utmost importance, and is maybe as important as the particle analysis. Bottle sampling is usually performed with a vacuum pump or by taking the sample from a tap directly into the bottle. There are many tribology instruments that are compatible to be utilized having bottled samples; some of these can be listed as: automatic particle counters, mesh blockage instruments, image analyzers, magnetic detectors, manual microscope, and devices required for gravimetrical methods.



Off-line Oil Sampling Methods

Figure 199 Different off-line methods of oil sampling; from left to right: sampling using a vacuum pump and a disposable plastic tube, sampling using a valve with protective cap [648]

all things considered, in-line and on-line techniques are employed to determine, for example, particle quantities in oils, water content and general oil condition like oil degradation based on infrared spectroscopy or electrical conductivity [495], [528]. Moreover, on-line technique can be used to collect wear particles by means of magnetic chip detectors, MCD [496]. More intensive assessment of the wear particles can then be carried out with microscopic methods. On-line instruments are situated in oil circulation systems and a part of the oil circulates through the measuring device. If the device is assembled in-line, then the whole oil volume will go through the measurement system. On the other hand, off-line technique requires taking a representative oil sample.

Particular considerations are required when the task is to sample grease. The grease sampler must be sure to get the sample from the working area of a bearing, which can sometimes be difficult. In most cases, this requires having direct access to the bearing cavity so that the sample can be taken from the load zone. Motors usually have a plug directly on the bottom of the bearing cavity from which a good sample of grease can be taken when applying new grease at the top. The old grease is expelled ahead of the new grease and the plug is normally not reinstalled until after the proper amount of grease is added and the motor is kept running for a few minutes to expel any excess lubricant. This prevents grease from being pushed through the seals and into the motor windings in the event of over greasing. Obtaining a representative sample from the bearing housing without removal of the cap depends on the location of a drain (i.e. sample port) in the housing itself.

6.12.3 Use and Applicability

Tribological testing is indeed applicable to all oil-circulated and oil-lubricated mechanical systems and the ones consisting of sliding and rolling surfaces. TT is particularly effective on equipment such as very slow-speed rotating machinery, and hydraulic systems where vibration monitoring capabilities may be limited or absent. To illustrate, contaminated oil in a hydraulic system can lead to binding or leakage which can be predicted employing tribological testing. It is also particularly effective on reciprocating machinery. Nevertheless, it cannot be concluded that these applications limit the use of tribological testing, or that they are even the most important applications. It is often high-speed rotating machinery where tribological testing may be most valuable as in such lubricated system contaminated oil can lead to a dramatic increase in wear. By and large, conditions of gears, gearboxes, bearings, motors, pumps, hydraulics and clean systems, air, ammonia and freon compressors, chillers, and hot oil systems can be effectively monitored and assessed by tribological testing techniques [70], [648].

As tribological testing evaluates machinery condition from an entirely different perspective than other nondestructive test and condition monitoring techniques, when the test results confirm other tests results, one can be more confident taking specific corrective maintenance action. In fact, other analytical techniques, such as vibration analysis, may help to pinpoint the particular machinery part in distress. In any case, predictive maintenance tools integrated together offer the maintenance engineer the best decision making tool. Moreover, production managers find it difficult to reject a shutdown request for maintenance with such clear evidence as a color photograph of large fatigue chunks, or cutting wear particles, especially when other tests outcomes are also confirming the problem.

One of most common applications of tribological testing is in inspection of diesel, gasoline and natural gas engines and thrusters. Wear debris analysis for a variety of engines has been used in conjunction with other techniques such as different types of spectrometry providing superior results. In engines, like other oil lubricated machinery, wear is indicated by increasing amounts of particles and by changes in particle size distribution, composition, and morphology. The effects of engine operating conditions on the wear of cylinders' liners, piston rings, and crankshaft main bearings have been successfully observed by both wear and oil analyses [389].

Particularly in the case of diesel engines, heat treatment of ferrograms distinguishes temper colors between low alloy (i.e. associated with the crankshafts) and cast iron (i.e. associated with the piston rings and cylinder liners), depending on the specific engine metallurgy. In fact, the most frequent wear-related problems in diesel engines are bore polishing, in which the cylinder wall is polished in spots to a mirror finish, and ring wearing. Both of these problems are linked to the piston deposits to some degree. These wear mechanisms increase the wear debris and can be easily detected by wear debris analysis, ferrography and spectroscopy [151].

Another application of tribological testing is in inspection of steam and gas turbines which can be subject to various failure mechanisms. Some of their failure modes develop very rapidly, whereas others can be detected hundreds of operating hours before a shutdown condition is reached. Most failures of gas turbines occur along the gas path. Gas path failures frequently increase wear particle size and concentration in the oil system, mostly due to the transmittal of imbalance forces to turbine bearings and other oil-wetted parts such as gears. The resulting bearing or gear wear particles are then detected by both wear and oil analyses (i.e. spectroscopy, viscosity, TAN and Karl Fischer tests).

Determining the exact source of wear problem can be difficult in a gas turbine because of complexity of the oil-wetted path. Typically several cavities, housing bearings, or gears will be force lubricated through individual return lines connected to a tank from which the oil is pumped passing through a filter and heat exchanger. Magnetic chip detectors or magnetic plugs are often installed to pinpoint the source of wear debris. However, chip detectors do not provide a warning until the wear situation is so severe that extremely large particles are being generated. By this time, the opportunity for predictive maintenance may be lost. Therefore, it is better to get use of other condition monitoring techniques to be able to identify the exact component under effect of wear [151].

6.12.4 Limitations and Pros

As mentioned before, tribological testing addresses friction, lubrication, and wear, which are fundamental in nearly all mechanical systems. Each of these has major cost impacts within industrial plants. For example, friction within mechanical systems directly translates into power loss. Lubrication costs include procurement, storage, filtration, installation, recycling, and disposal. Wear is the primary characteristic defining the end of life for plant machinery and leads to costs of maintenance, replacement, and production outage. Friction, lubrication, and wear are interactive and cannot be separated [200], [201], [309].

A successful tribological testing necessarily addresses the three mentioned factors from the perspective of their total cost to the industrial plant. Such programs for industrial plants have been reported to save more than 200,000 € per year from extended oil drain intervals, avoided maintenance actions, and production uptime. The benefits from more comprehensive tribological testing efforts have been documented as much as 1,000,000 € per year for very large plants. The portions of such a large saving are consisted of 70% equipment failure, 20% lubricant procurement, 5% material handling, and 5% electrical power [215]. On the other hand, Tsang states the following limitations of tribological testing in a condition based maintenance program while underling its benefits [630]: high equipment costs, being usually a laboratory based procedure, reliance on acquisition of accurate oil samples and skills needed for proper interpretation of data. Garvey and Fogel state that an effective industrial tribology program is much more than just oil tribological testing [214]. TT reveals important information about the condition of machinery, lubricants, and contamination in the lubricants. Substantial savings are attainable through tribological testing. However, much greater benefits are achievable via a condition and reliability based tribology program which intakes the factors listed in the next page.

- Achieved selection of optimal lubricants
- Improved capacity by avoiding breakdowns
- Improved overall indication of system health
- Achieved machine and lubricant life extension
- Realized failure reduction through root cause analysis
- Integrated with other condition monitoring technologies
- Employment of value based application of tribology technologies
- Applied quality assurance for lubricants, filters, breathers, refurbishment
- Known condition of equipment - thereby providing status of plant capacity

On the whole, production and profits can either benefit or be hurt by the approach that is taken towards tribology. Industrial plants that are the benchmark performers in tribology for their industry take credit for large savings each year. These savings can result directly from TT information as it reveals hidden information about machine wear condition, lubricant chemistry, or lubricant contamination. Moreover, they can be resultants of effective lubricant procurement, storage, handling, and disposal practices, as well as root cause failure analysis, and resulting corrective measures. Indeed, one of the most important aspects of an effective TT program is the way it is implemented by people; if they understand tribological information, if they know what to do with that information, and if they take ownership for the program and its results. Walsh expresses that although the cost of tribological testing supplied by the lubricant suppliers may be superficially attractive, there is often a concealed premium that is being paid by the loss of valuable information on machine condition assessment and the ability to prolong the life of the lubricant [648]. Hence, end users are usually getting the best service by working with an independent tribology lab, rather than their lubricant supplier. In fact, the incremental benefits achieved from using an independent tribology lab will almost always cover the involved costs.

Table 56 Synopsis of tribological testing

Pros	▪ No serious safety hazard ▪ Sometimes can be undertaken online ▪ No machine or equipment preparation ▪ Accurate and permanent test record obtained ▪ Evaluation of inaccessible areas and overall condition ▪ Wear is discovered before it can cause stoppage or severe system damage ▪ Availability increase by rising operational life time of machinery and equipment ▪ Cost reduction by avoiding needless oil and lubricant changes or preventing failures due to their lack
Limitations	▪ Mobility ▪ High skills are required ▪ Laboratory based procedure ▪ Relatively expensive equipment ▪ Immediate results are not usually achievable ▪ Reliance on acquisition of accurate oil samples ▪ The process is sometimes messy (depending on method used)
Equipment	▪ Viscometers, spectrometers, oil analyzers, particle counters, and microscopes and so on.
Detectable failure	▪ Potential failures of machinery or equipment components due to lack of/incorrect use or contaminations in the lubricants and oils, and different types of machinery wear
Discontinuity type	▪ Following degradation phenomena or discontinuities can be identified: abrasion, adhesion, cavitation, corrosion, erosion, fatigue, fretting and wear
Relative inspection cost	▪ Analysis of a “single” oil or lubricant sample costs from 5 € to 50 € depending on the analysis level. ▪ There is no more cost-effective CM/NDT technique for plants having a large number of rotating machinery or high euro machinery using circulating lubricant. ▪ Considering high equipment replacement cost, labor and downtime costs associated with a bearing or gearbox failure, a single failure prevented by undertaking TT can easily pay for sustaining a standard TT program for several years.

6.13 Ultrasonic Testing

Ultrasonic testing (UT) employs an extremely diverse set of methods based upon the generation and detection of mechanical vibrations or waves within test objects. The test objects are not restricted to metals, or even to solids. The term ultrasonic refers to sound waves of frequency above the limit of human hearing. The velocity of ultrasonic waves traveling through a material is a simple function of the material’s modulus and density, and thus ultrasonic methods are uniquely suited to materials characterization studies. In addition, ultrasonic waves are strongly reflected at boundaries where material properties change, and thus are often used for thickness measurements and crack detection. Recent advances in ultrasonic techniques have largely been in the field of phased array ultrasonics, now available in portable instruments.

6.13.1 Conception

Ultrasonic, or ultrasounds, are defined as sound waves that have a frequency level above 20 kHz. Sound waves in this frequency spectrum are higher than what can normally be heard by humans. Non-contact ultrasonic detectors used in predictive maintenance detect airborne ultrasound. The frequency spectrums of these ultrasounds fall within a range of 20 to 100 kHz. Ultrasounds travel a relatively short distance from their source and in a straight line, and will not penetrate solid surfaces. Most rotating equipment and many fluid system conditions will emit sound patterns in the ultrasonic frequency spectrum.

Changes in these ultrasonic wave emissions are reflective of equipment condition. Ultrasonic detectors can be used to identify problems related to component wear as well as fluid leaks, vacuum leaks, and steam trap failures. A compressed gas or fluid forced through a small opening creates turbulence with strong ultrasonic components on the downstream side of the opening. Even though such a leak may not be audible to the human ear, the ultrasound will still be detectable with a scanning ultrasound testing device [590].

As explained, ultrasonic testing is a nondestructive testing technique that uses sound energy moving through the test specimen to detect flaws. The sound energy passing through the specimen will be displayed on a Cathode Ray Tube (CRT), a Liquid Crystal Display (LCD) or video/camera medium. Indications of the front and back surface and internal/external conditions will appear as vertical signals on CRT screen or nodes of data in computer test program. The amount of reflection that occurs when a sound wave strikes an interface depends largely on the physical state of the materials forming the interface and to a lesser extent on the specific physical properties of the material. For instance, sound waves are almost completely reflected at metal-gas interfaces; and partial reflection occurs at metal-liquid or metal-solid interfaces.

As ultrasonic energy (i.e. pulse) travels through a test sample and strikes a crack or some other anomaly, it will be reflected, that is, the incident beam strikes the interface resulting in a reflected beam returning in the opposite direction in the same material and a refracted or transmitted beam passing through the interface into the other material. All ultrasonic methods have the following basic operating principle: High frequency ultrasonic energy (i.e. from a few kHz to some MHz) is generated in the part being inspected. This energy causes vibration at molecular level with the material. This energy travels in the part. The ultrasonic energy is modified (e.g. reflected, scattered, attenuated, etc.) as it interacts with the object being inspected. Then, the modified ultrasonic energy is received by UT equipment that can record and analyze the pertinent parameters of that energy.

1. *Lamb Waves Inspection:* When ultrasonic energy is introduced into relatively thin plates, it is propagated as Lamb waves. Lamb waves have multiple or varying wave velocities. The velocity depends on material characteristics, plate thickness, and frequency. Lamb waves are generated when the angle of incidence is adjusted so that the velocity of the longitudinal incident wave equals the velocity of the desired mode of the Lamb waves. In order to experimentally determine the optimum Lamb wave mode, reference standards of the material of interest are invaluable. Adjusting the search unit angle for maximum peak amplitude will determine the proper incidence angle for that material at that test frequency [351].

2. *Pulse-Echo Inspection:* It is the most common guided waved testing. Guided wave inspection is performed at low frequencies (i.e. typically 0.1 to 1 MHz) and low incident angles. In a pulse-echo configuration, a flaw must have some minimum cross-sectional area in the structure wall in order to create a detectable reflection. For instance, a defect that has length but no measurable width, such as longitudinal gauge, would be difficult to detect if the length happens to be parallel to the direction of the guided wave propagation. Indications of flaws are detected by measuring the time arrival and/or the signal strength of sonic echoes. For example, wall thinning caused by corrosion and/or erosion would cause the returning echo to arrive earlier than expected travel time required for the back surface [500].

3. *Tip-Diffraction Inspection:* Tip-diffraction, also known as time-of-flight-diffraction (TOFD), is the only ultrasonic inspection method that has been standardized. It differs from conventional ultrasonic pulse-echo examinations in that the reflected energy normally compared to a reference reflector is not used for the classification of defects. The actual size is derived from the diffracted signals generated in all directions at the extremities of the defect. Signal arrival times, distance between the transducers, part thickness, and angle of the ultrasonic beam centerline are combined and geometry allows the flaw size to be identified. This results in a highly accurate measurement. TOFD is most effective if the flaw is directly between the transducers. Both planner and volumetric defects can be measured accurately. This inspection method is predominantly used for crack sizing and weld inspection [119], [351].

6.13.2 Tools and Techniques

Ultrasonic detection devices are becoming more widely used in detection of certain electrical system anomalies. Arcing/tracking or corona all produce some form of ionization that disturbs the air molecules around the equipment being diagnosed and produces some level of ultrasonic signature. An ultrasonic device can detect the high-frequency noise produced by this effect and translate it, via heterodyning, down into the audible ranges. The specific sound quality of each type of emission is heard in headphones while the intensity of the signal can be observed on a meter device to allow quantification of the signal.

In addition to translating ultrasonic sound waves into frequencies heard by the human ear or seen on a meter face, many ultrasonic sound wave detectors provide the capability to capture and store the detectors output. Utilizing display and analysis software, a time waveform of the ultrasonic signature can then be visually displayed. This functionality increases the technology's capability to capture and store quantifiable data related to a components operating condition. Ultrasonic signature information can be used to baseline, analyze, and trend a component's condition. In contrast to a technician's subjective analysis of a component's condition using an audio signal, many ultrasonic anomalies indicative of component problems are more easily defined using a signature profile.

As McLay and Lilley assert, while a manual ultrasonic operator may suffer from the 'boredom factor', and UT automated scanning technique cannot overlook or fail to register individual signals, provided that its procedure has been properly adhered to [421]. Ultrasonic equipment range from the very simple scanning frame with dual axis potentometric probe positional feedback to fully programmable robotic scanners; and from a simple black-and-white plotting system to sophisticated processor-controlled color display formats with data storage facilities.

Ultrasonic pulse-echo testing is performed with one transducer doing both generation and reception, or with two transducers (i.e. a transmitter and a receiver) placed next to each other on the same side of the test piece. Either configuration requires access to only one side of the structure. In order to receive and ultrasonic signal in the pulse-echo mode, the energy must be reflected off of some feature (e.g. a discontinuity or the back wall) of the test object and back towards the transducer used for generation. This method is usually used for wall thickness measurement or flaw detection, and can be used for some flaw sizing techniques [501].

Pulse-Echo Ultrasonic Inspection Technique

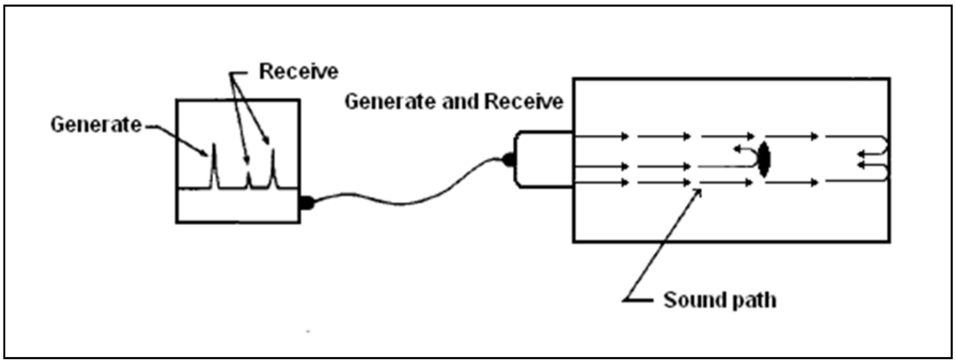


Figure 200 Pulse-echo ultrasonic technique for inspection of an internal discontinuity

Tip-diffraction ultrasonic technique involves using a pair of angled compression wave probes, set on either side of a defect and facing each other. One probe acts as the transmitter and the other probe acts as the receiver. The beam and the amplifier characteristics are selected as wide and even distribution of ultrasonic energy as possible in the through-wall plane. The first signal sensed by the receiver is the upper edge of the beam, which, ultrasonic testing terminology, is referred to as the lateral wave. This signal represents the shortest path between the two probes, and on a flat surface this represents the material outer or scanned surface. Part of the beam will be reflected from the inner surface or back wall of the object. This signal arrives later in time that the lateral wave. With prior knowledge of the material velocity and the physical separation between the two probes, the material thickness can be accurately and reliably calculated. The reflection obtained from the defect will arrive at the receiver before the one of back wall [119].

Tip-Diffraction Ultrasonic Inspection Technique

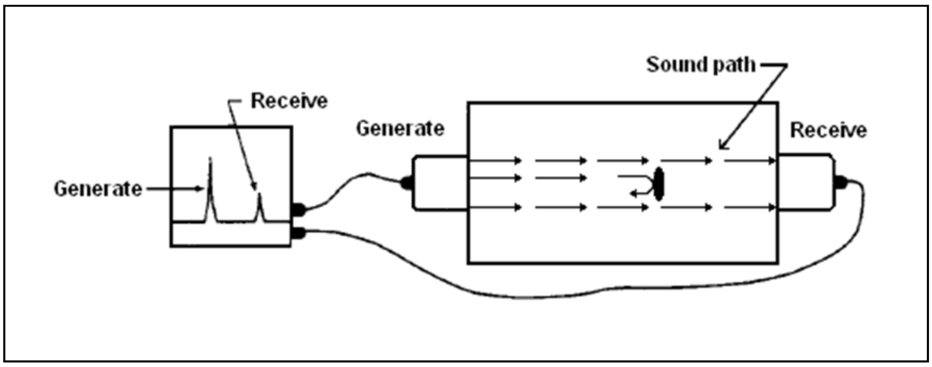


Figure 201 A conceptual drawing of tip-diffraction ultrasonic technique for inspection of an internal discontinuity; there are two transducers required each on one side of the structure wall

In practice, to direct ultrasound at a particular angle or to couple it into an irregular surface, transducer positioning fixtures and sound-coupling shoes are employed. Shoes are made of a plastic material that has the necessary sound-transmitting characteristics. Positioning fixtures are used to locate the transducer at a prescribed point and can increase the sensitivity of the inspection. Moreover, it is important to note that inspection with ultrasonics is limited to the part in contact with the transducer. A layer of couplant (e.g. water, glycerin, oil and grease) is required to couple the transducer to the test piece as ultrasonic energy will not travel through air [439].

Use of Positioning Fixture for UT Transducer

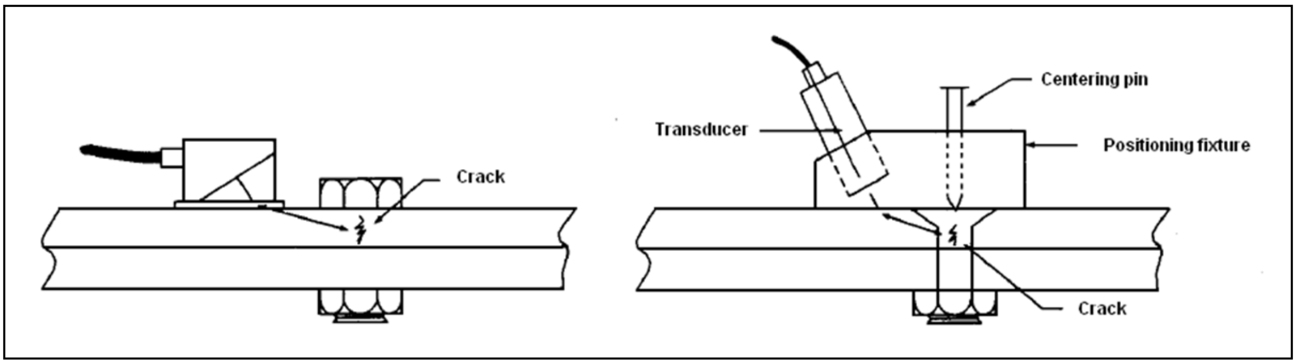


Figure 202 Application of transducer fixture in UT; in hand positioning of transducer the minimum detectable crack size is 4-8 mm while using a fixture brings this size down to 2-4 mm

6.13.3 Use and Applicability

Outside of visual inspection, ultrasonic testing is probably the most commonly used NDT method, widely used by industry for quality control and maintenance purposes. Major uses include flaw detection and wall thickness measurements. Using ultrasonic techniques, it is possible to detect flaws and determine their size, shape and location. It is also possible to measure the thickness of pipes and vessels with ultrasonic transducers. Wall thickness measurements are especially important in corrosion studies where corrosion can cause a uniform reduction in wall thickness over a period.

Ultrasonic analysis is one of the less complex and less expensive predictive maintenance technologies. The required equipment is relatively small, light, and easy to use. Measurement data is presented in a straightforward manner using meters or digital readouts. The cost of the equipment is moderate and the amount of training is minimal when compared to other predictive maintenance technologies. Since ultrasounds travel only a short distance, some scanning applications could present a safety hazard to the technician or the area of interest may not be easily accessible. In these applications, the scanning device is generally designed with a gain adjust to increase its sensitivity, thereby allowing scanning from a greater distance than normal.

Variety of instrumentation exists to perform different automated scans of wall thickness and provide digital, hard copy and video images. It is also possible to permanently install ultrasonic transducers for continuous monitoring in a particular location. On-line or in-line inspection can be achieved using intelligent pigs. Pigs are devices that are inserted into a pipeline and driven through by product flow. Intelligent pigs are instrumented to nondestructively survey the condition of the pipeline while it is in operation. Data is acquired and downloaded when the pig is retrieved to provide information on the nature and location of defects [94], [145].

Lamb waves, more specifically, are used to detect a change in section thickness in plate and sheet. These changes in thickness, or loss of wall, are often due to corrosion. Also, large laminations in rolled products may be detected with Lamb waves. Where the full pipe or plate thickness will excite a certain group of Lamb wave modes, a thinner section will excite a different group. Lamb waves are utilized to inspect metal plates and bars as well as composite materials, to detect laminar defects near their surface and to bond-test thin laminar structures. Lamb waves are also used to perform inspection over long distances, usefulness in accessible areas and lack of necessity to remove extensive amount of pipe insulation [15], [387], [474], [526], [655].

Pulse-echo is an effective ultrasonic inspection method on components with complex geometries. It uses reflected signals to evaluate an object. Most pulse-echo instruments operate in a similar manner, by digitizing all full ultrasonic wave forms as the angled shear wave probes are scanned in a raster fashion over the material surface and can be displayed in real time on a monitor as colored or gray-scale images. As the wave forms are collected by scanning in two dimensions, and the third dimension is represented by the ultrasonic range, a three-dimensional block of ultrasonic signals is available for off-line processing to create elevations from above, from the side, or end of the structure. In this way, flaws are imaged and their signal patterns are more readily distinguished from geometrical responses [351], [500], [585].

In tip-diffraction technique, the depth of penetration of anomalies can be very accurately measured since the probes are situated on the parent material. The ultrasonic waveform is fully digitized and stored in its entirety. The probe is then moved 1 mm and another waveform is then collected. These waveforms are plotted and shown via a screen on or remote from the measuring equipment. This technique is responsive to planar and volumetric buried and surface breaking flaws of all orientations, anywhere in the material. This means that service and service-induced flaws such as stress corrosion cracking can be detected and monitored for growth. The TOFD technique is usually performed using either a handheld scanner that uses an encoding wheel or a magnetized scanner. The mathematics involved is relatively complex, and most TOFD systems automate data analysis.

Ultrasonic thickness measurements are used for many applications, such as: checking part thickness when access to the back side is not available; checking large panels in interior areas where a conventional micrometer cannot reach; and in maintenance inspections for checking thickness loss due to wear and/or corrosion. Dependent upon the instrument used and the material under test, material thickness from 0.1 to 500 mm and more can be measured with pulse-echo instruments designed specifically for thickness measuring. Coming to the crack or flaw detection and identification of its size and characteristics advance TOFD instruments are usually used. Nevertheless, some special UT instruments are employed for other testing and inspection purposes in recent years.

Nowadays, another important application of different ultrasonic testing methods is in leak inspection. The flow of a pressurized gas through a leak produces sound of both sonic and ultrasonic frequencies. If the gas leak is large, the sonic frequency sound it produces can probably be detected with the ear or with such instruments as stethoscopes or microphones; on the other hand, the ear and these instruments have limited ability to detect and locate small leaks. Ultrasonic leak detectors are frequently used to detect leaks that cannot be detected by the above methods, because they are very sensitive to ultrasonic energy and, under most conditions, background noise at other frequencies does not affect them.

Ultrasonic energy in the relatively low-frequency range of 30 to 50 kHz travels easily through air; hence, an ultrasonic leak detector can detect leakage with the probe located away from the leak. Some typical applications for the ultrasonic leak detector in industry are: fuel tanks or vessels pressurization tests, air ducts and air conditioning systems, tire pressure retention, electrical discharge, gas lines and valves, internal leaks in hydraulic valves and actuators, fuel cell testing, identifying cavities in hydraulic pumps, arcing in wave guides, and etc.

6.13.4 Limitations and Pros

One of the limitations of UT use is for multi-layered materials. As these materials are often highly attenuating and anisotropic, it is often difficult to transmit and receive the necessary sonic signals that contain the UT information. Large reflections are produced when ultrasound is directed from one medium to another with very different acoustic impedance. Furthermore, sonic energy can be channeled or directed along self-preferential directions, in other words, not necessarily those directions useful in the inspection.

Pulse-echo method is commonly used for in field applications for measuring wall thickness. An advantage of pulse-echo systems is that flaws of different depths can be distinguished from one another using geometry and time-based considerations. However, while detecting the presence of a discontinuity is straightforward, interpretation and evaluation of the resulting data can be difficult. Most flaw detection analysis is based on amplitude of the reflected signal. This amplitude is a function of flaw parameters such as orientation, type, depth and location.

For instance, if the ultrasonic beam is introduced at 45 degrees from the object's surface and the flaw is also at 45 degrees, then scanning in one direction will create almost no reflection as the beam travels directly perpendicular to ultrasonic beam centerline. A priori knowledge of the type, location and orientation of flaws that are most common in a specific application is important for proper flaw interpretation and evaluation.

TOFD can be used for very accurate sizing of a flaw, and does not require any 'compensation' factors. However, the lateral wave travels directly between two transducers, and can therefore obscure of near-surface flaws. The depth of the lateral wave increases in convex surfaces because the straight line between the transducers is deeper. The lateral wave does not propagate across concave surfaces; though, 'backscatter' TOFD reduces lateral wave problems [119], [469].

Moreover, TOFD may be more sensitive than other ultrasonic inspections to in-service conditions, and are therefore more likely to require removing the system being inspected from service, but many sizing applications can be done while a system is in service. In addition, this technique needs significant inspector training more than that needed for thickness gauging or flaw detection by other ultrasonic techniques [560], [561].

The merits of advanced computerized ultrasonic techniques mean that not only the minimum thickness is more reliably examined and reported, but often the cause of the problem may be determined. A decade ago, mechanized ultrasonic systems were considered expensive, cumbersome and inflexible. However, with ever-faster computers and data acquisition systems combined with increasing acceptance of these systems in specifications, these barriers are rapidly being overcome. Now, the resultant wave forms can be digitized, stored on disk, and displayed on a video screen as images which can be used for accurate sizing and monitoring of any indications of wear or damage.

Table 57 Synopsis of ultrasonic testing

Pros	▪ Immediate results ▪ Little part preparation ▪ Capable of detecting internal defects ▪ Sensitive to very small discontinuities ▪ Portable and suitable for field inspection ▪ Very sensitive to planar type discontinuity ▪ Information on size of detected discontinuity ▪ Requires only one-side accessibility of test item ▪ Wide range of materials and thicknesses can be inspected		
Limitations	▪ Couplant usually required ▪ Unsuitable to inspect castings ▪ Rough surfaces interfere with test ▪ Surface must be accessible to probe ▪ High degree of skill required for set-up and interpretation ▪ Incapable of detecting defects whose plane is parallel to the sound beam direction ▪ Unreliable for surface and subsurface discontinuity due to pulse and signal interfaces		
Equipment	▪ Transducers, couplant, transmitters and a small data acquisition/processing system ▪ Automated scanning and single frequency or multi frequency equipment are also available		
Discontinuity types	▪ Burst ▪ Crack ▪ Pitting ▪ Fatigue ▪ Erosion ▪ Porosity	▪ Disbond ▪ Fracture ▪ Inclusion ▪ Corrosion ▪ Stress crack ▪ Delamination	▪ Fatigue crack ▪ All primary flaws ▪ Subsurface crack ▪ All secondary flaws ▪ Stress-corrosion crack
Discontinuities size	▪ Very small discontinuities can be detected		
Relative inspection cost	▪ It is relatively inexpensive, e.g. an UT hand-held scanner with its auxiliary equipment costs 800 € to 8000 € ▪ Relative minimal expense combined with large savings opportunities will most result in an equipment payback period of 6 months or less		

6.14 Vibration Analysis

Vibration analysis (VA) is one of the most commonly used technologies to test and monitor the machinery condition. VA involves measuring vibration levels near rotating or reciprocating parts in machinery. The principle behind vibration analysis is that a rotating component which starts to deteriorate or disintegrate will produce higher vibration levels at the frequencies related to the speed of rotation. These levels can be monitored and warning can be given of a failure in a component. The amplitude of each distinct vibration component will remain constant unless there is a change in operating dynamics of the system. VA can be used on individual components to identify gear and bearing problems or it can be used on an entire system to identify a global vibration problem. Comparison of the vibration spectra of new equipment versus equipment that has been used will provide the information required to make a decision when maintenance intervention is required.

6.14.1 Conception

Vibration can be described as a periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed or the state of being vibrated or in vibratory motion as in oscillation or, quivering or trembling motion. The key factors to be fished out from the description are: vibration is motion and this motion is cyclic around a position of equilibrium. Different rotating or reciprocating parts of machinery generate their own distinctive pattern and level of vibration. The level and frequency of these vibrations are different and of course a human touch is not sensitive enough to discern these differences. This is where vibration detection instrumentation and signature analysis software grant the necessary sensitivity. Sensors are used to quantify how rough or smooth the machine is running. Mechanical vibration can be measured in terms of the following factors [152]:

- *Displacement:* Total distance traveled by the vibrating part from one extreme limit of travel to other extreme limit of travel. This distance is also called as ‘peak-to-peak displacement’.

- *Velocity:* A measurement of the speed (i.e. rate of change of displacement) at which a machine or machinery component is moving as it undergoes oscillating motion.

- *Acceleration:* Rate of change of velocity; recognizing that vibrational forces are cyclic, both the magnitude of displacement and velocity change from a neutral value to some maximum.

If velocity is kept constant over frequency related displacement and acceleration can be assumed as the way shown in the below figure. This is important as it means that displacement is the most sensitive factor to be measured at low frequencies. However, sensitivity of acceleration measurement exceeds than that of the other factors at higher frequencies. In other words, for an effective VA, displacement measurement should be used at low frequencies, and acceleration should be used at high frequencies. For machinery condition monitoring displacement and velocity are measured at frequencies under several hundred hertz and acceleration measurement is used at higher frequencies.

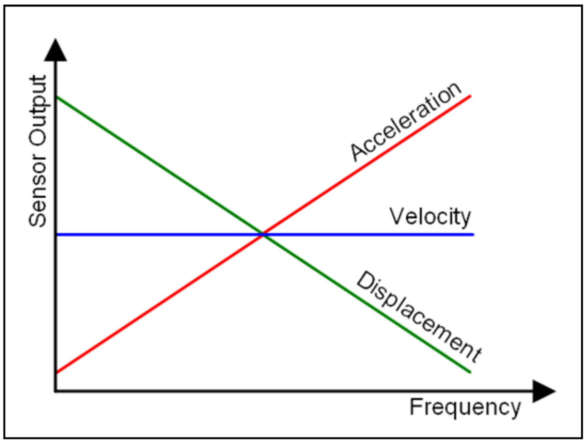

Displacement, Velocity and Acceleration

Figure 203 Relation between constant velocity and related displacement and acceleration in VA

Vibration waves are represented and characterized with three different parameters of amplitude, frequency (i.e. period) and phase (i.e. time difference). Amplitude shows the magnitude of the waveform. Taking sound as an example, loud sound has large amplitude. Frequency represents the number of wave periods repeated in one second and is defined in unit of hertz [Hz]. One period of a wave is represented as an angle of 360° or 2π radians. The position of a peak, if measured at a particular point in time, may differ between waves of the same frequency. The difference in the peak position of a given waveform from the reference waveform is usually expressed as a quantity called a phase difference. The phase is considered negative if the particular peak lags behind the corresponding peak in the reference waveform, or positive if it comes after the corresponding peak [203].

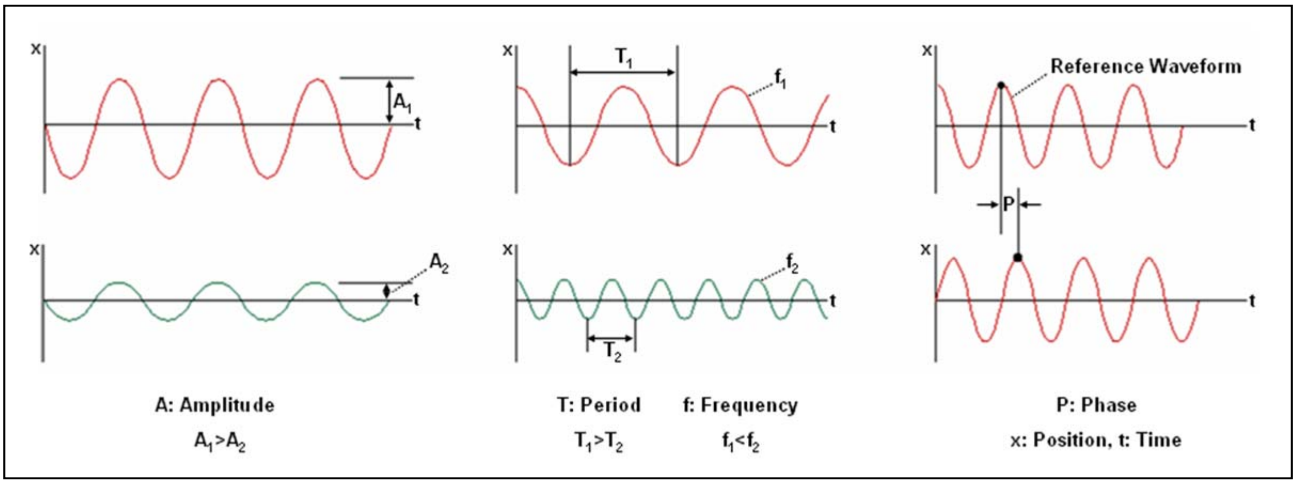

Amplitude, Period and Phase

Figure 204 Amplitude, period and phase factors that characterize a vibration wave

The vibration analysis consists of vibration measurement and its interpretation. Firstly, vibration signals are collected by means of the vibration analyzer equipped with a sensor in the time domain then, these signals are converted into frequency domain by different processing methods, and the information gained from the vibration signals can be used to predict catastrophic failures, to reduce forced outages, to maximize utilization of available assets, to increase the life of machinery, and to reduce maintenance costs related to health of machinery.

To illustrate, one can consider the figure below. A vibration sensor (e.g. an accelerometer) has been installed on a bearing of a motor system with multi rotary components and composite time-axis vibration waveforms are can be monitored. With use of different VA tools such as Fast Fourier Transform (FFT), frequencies corresponding to the vibration generated from each position are determined from the construction of the machine.

Vibration Analysis of a System with Multi Rotary Components

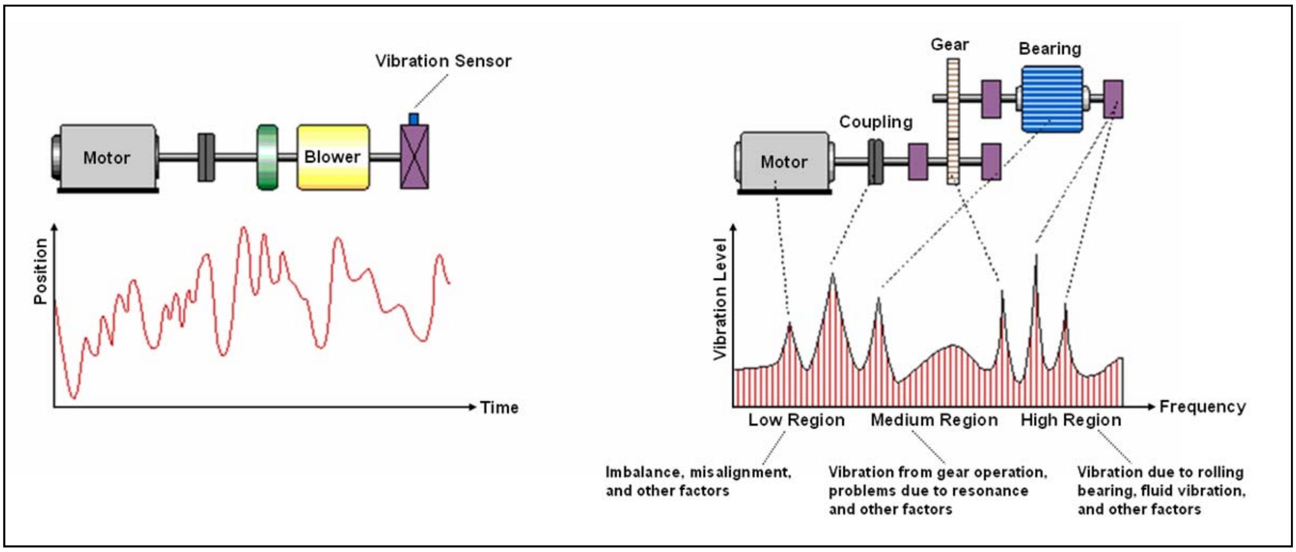


Figure 205 On the left: Vibration monitoring of a motor system by use of a sensor, which has been mounted on a bearing. This provides composite time-axis waveforms to be analyzed. On the right: A conceptual diagram showing the possible resultant information of VA of the waveforms using FFT analyzing methodology.

Formerly, when maintaining and controlling machinery and diagnosing anomalies, a measure of the entire vibration was used to be obtained, that is, an overall value was measured with an instrument such as a vibration meter. However, since an overall value could only be used to determine whether the vibration is strong or weak, the actual location of anomaly could not be identified. By introducing different VA techniques such as FFT a new era has been started in which not only it is possible to monitor the waveform change over time (i.e. time-axis waveforms) but also to identify the cause of that change plus the exact position of the anomaly in a multi-component system. It is essential to keep in mind that in early stages of failure or for slight anomalies, the overall value of time-axis waveforms shows very little change, hence, making it difficult to detect the failure; contrastingly, frequency analysis (i.e. observing the waveform in the frequency domain) eliminates the mentioned pitfall [152].

On the whole, there exist two different major methods through which VA can be realized and used; these are centered on the way the vibration signals or signatures are produced and called free-vibration and forced-vibration analyses [464], which are briefly explained in the followings.

1. *Free-vibration Analysis:* This nondestructive evaluation method is based on the principle that all machinery systems, and more exclusively rotating or reciprocating parts, produce vibration. When a machine is operating properly, this vibration is small and constant; however, when faults develop and some of the dynamic processes in the machine change, the vibration spectrum also changes [13]. For this reason, vibration monitoring and measurement is known as a powerful tool in machinery condition monitoring. The failures of rotating and reciprocating machineries can be very critical because these lead to machinery damage, production losses and personnel injury. The free-vibration analysis is a technique, which is being used to track self-generated machinery vibration and to trend deteriorations in order to reduce maintenance costs and downtime simultaneously [512]. Most of the defects encountered in the rotating machinery give rise to a distinct vibration signature (i.e. vibration pattern) and, hence, mostly faults can be identified using vibration signature analysis techniques. Vibration signal analysis has long been used as a diagnostic tool for fixed, rotating machinery such as motors, pumps, compressors, fans, turbo-machinery blades, and shafts, which are usually designed to operate optimally at fixed speeds (i.e. rotational or angular speed). Increasing or decreasing the operational speed often causes the machinery to run at a speed that corresponds to a natural frequency of the system.

In general, any speed which is associated with very high vibration is often called a critical speed. Running at the critical speed produces severe vibration. Unchecked, this severe vibration can result in premature failures, broken parts and even catastrophic breakdowns. In the simplest case, a change in the vibration amplitude is often indicative of a damaged rotor blade or a faulty bearing. Acceptable levels of vibration are often included in the specification sheets provided by the manufacturer. An increased vibration level is only an indication of a problem; relating it to a specific fault is much more complex [12], [121].

Resonance Vibration Signal

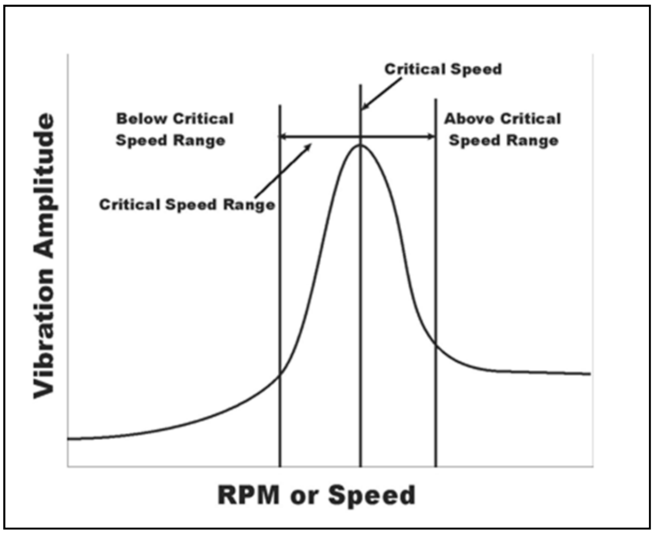


Figure 206 Characteristics of a resonance vibration signal regarding the critical speed

2. *Forced-vibration Analysis:* This technique, which is also known as dynamic method, involves application of a known vibration to an object or structure and observation of its vibrational response. The dynamic response is sensitive to the presence of flaws. It is also possible to use dynamic methods to determine variations in material properties. Two different schemes are usually used in dynamic testing: a measurement of natural (i.e. resonant) frequency and measurement of rate of attenuation. Indeed, objects or structures can vibrate at different natural frequencies. These frequencies are a function of geometric parameters, physical constants (e.g., elastic modulus, density, and Poisson's ratio) and end constraints. Modes of vibration include flexural, torsional, longitudinal, radial, diametrical and annular.

   Modal analysis refers to study of the natural frequencies, damping values and mode shapes of physical systems. Measurement of natural or resonant frequency involves application of a vibration force and the frequency at which natural frequency is matched is determined. Resonant frequency tests require that the object be supported at the nodes for the mode of vibration under consideration. The vibration force is applied by a piezoelectric transducer, electromagnetic vibrator or other means of inducing vibration. The vibration is detected by some form of pickup. A range of physical properties can then be calculated based on the measured resonant frequency. Elastic properties, and resultant resonant frequencies, are affected by flaws [203].

   Use of resonant frequency techniques to detect flaws or damage in structures requires some form of comparing the response of the test structure to one that is known to be sound and using this information to ascertain the nature and location of damage. This is where modal analysis becomes applicable in both theoretical and experimental forms. The deviations in measured global vibrational response of the structure must be correlated with localized damage. In order to achieve this, it is necessary to consider the local response parameters such as mode shape data. The other scheme is measurement of attenuation, or damping, rate. In this method an object is induced to vibrate in one of its natural frequency modes by a vibration pulse. The pulse is then stopped and. the subsequent decay in vibration is measured. The specific damping capacity is then determined from the decay curve. Since the damping capacity is increased by the presence of flaws, this method can be used for nondestructive evaluation of objects.

6.14.2 Tools and Techniques

As it has been mentioned, vibration can be characterized in terms of three parameters: displacement, velocity and acceleration. Various transducers are available that will sense and provide an electrical output reflective of these parameters. The specific unit of measure to best evaluate the machine condition will be dependent on the machine speed and design. Several guidelines have been published to provide assistance in determination of the relative running condition of a machine. However, it has to be underlined that the values defined in these guidelines are not absolute vibration limits above which the machine will fail and below which the machine will run indefinitely. It is impossible to establish absolute vibration limits. Though, in setting up a predictive maintenance program, it is necessary to establish some severity criteria or limits above which action will be taken. Such charts are not intended to be used for establishing vibration acceptance criteria for rebuilt or newly installed machines. They are to be used to evaluate the general or overall condition of machines that are already installed and operating in service [590].

Depending on the application, a wide variety of hardware options exist in the world of vibration. Although not complicated, actual hardware requirements depend on several factors. The speed of the machine, on-line monitoring versus off-line data collection, analysis needs, signal output requirements and etc. will affect the type of proper equipment. Regardless of the approach, any vibration program will require a sensing device (i.e. transducer) to measure the existing vibration and translate this information into some electronic signal. Transducers are relatively small in size and can be permanently mounted or affixed to the monitoring location periodically during data collection. In some cases, the actual translation of the vibration to an electrical signal occurs in a handheld monitoring device. A metal probe attached to a handheld instrument is held against a point of interest and the instrument translates the motions felt on the probe to some sort of electrical signal.

Other portable devices utilize a transducer and handheld data collection device. Both styles provide some sort of display where the vibration magnitude is defined. Styles and equipment size vary greatly, but equipment is designed to be portable. Besides, many manufacturers provide instrumentations that perform signal analysis as well. Some equipment is a stand-alone design and performs analysis in the field independent of computer interface while other equipment designs interface transducers directly with a PC where analysis software is utilized to interpret the signal data [590].

To make a clear-cut and provide an example of vibration tools, one can name accelerometers, which sense vibration that commonly found in most industrial machinery. Applications for acceleration and velocity sensors include machinery health monitoring of motors, fans, pumps, gearboxes, blowers, machine tool spindles, compressors, chillers, rollers, and mixers. Maintenance professionals use accelerometers for predictive maintenance to lower overall cost and increase machinery performance. Accelerometers have wide range of varieties that includes velocity sensors for machinery health monitoring, high frequency and low frequency accelerometers for high and low speed monitoring, high temperature sensors for extreme environments, dual output sensors which measure vibration and temperature, and tri-axial accelerometers which measure vibration along three axes [205].

Sample Accelerometers

Figure 207 Different types of accelerometers for a variety of applications in vibration monitoring [WS109]

Coming to the issue of techniques, in practice there exist two general approaches, which are named as broadband and narrowband vibration trending. Broadband Vibration Trending monitors only the overall machinery condition. Readings of the overall vibration energy (i.e. 10 Hz to 10 kHz) are taken from selected points on a machine. The data is then compared to baseline readings. An alarm is triggered when a reading exceeds this limit. Alternatively, vibration readings are compared to vibration severity charts to determine the relative condition of the machine. Microprocessor-based instrumentation is used to measure and monitor the root-mean-square (RMS) level of the vibration [546], [630].

In narrowband Vibration Trending, the total energy across a specific bandwidth of vibration frequencies during a time domain is tracked to monitor the health condition of specific machine components or failure modes. Such data can be transformed into the frequency domain so that the vibration at each frequency component can be measured. The frequency plot (i.e. vibration signature) provides a visual representation of each frequency component generated by the machine. When the vibration signatures taken at different times are arranged in chronological order in a cascading on a 3D plot, a waterfall plot of the machine is formed. Accordingly, anomalies can be easily detected by noting that the vibration signatures have changes over time [630].

On the whole, the level of sophistication in measuring vibration can vary from a technique as simple as routinely putting the hand on a machinery component and relying on ‘the old gut feeling’ to complex real-time spectrum analysis. The level of complexity varies depending on the results desired. In general, vibration analysis relies heavily on comparison to data history. This type of vibration monitoring and analysis has seen fairly extensive use in all areas of manufacturing and production industry. Nevertheless, VA requires a set of baseline measurements be taken so that any changes in operating performance can be compared against them.

6.14.3 Use and Applicability

Different vibration monitoring techniques can be used to detect fatigue, wear, imbalance, misalignment, loosened assemblies, turbulence and etc. in machinery with rotating or reciprocating parts such as bearings, gear boxes, rotating shafts, pumps, transmissions, motors, engines, and turbines. The operation of such mechanical systems releases energy in the form of vibration with frequency components which can be traced to specific parts in the system. The amplitude of each distinct vibration component will remain constant unless there is a change in the operating dynamics of the system [630]. Misalignment is probably the most common cause of rotating machinery malfunction. A poorly aligned machinery part can cost a factory 20% to 30% in machine downtime, replacement parts, inventory, and energy consumption. A large payback is often seen by regularly aligning machinery. Operating life is extended and process conditions are optimized. Vibration signatures are widely promoted as a useful tool for studying machine malfunctions [210]. Indeed, the amplitude of vibration of a rotating part is a direct indication of the balance of the part, and hence the wear and, of course, the life of the part. It is considered that the information available from within a vibration spectrum may easily exceed that of other parameters (with the exception of debris monitoring).

A vibration signature contains a great deal of information and is very noisy. Through signal conditioning, the desired signals are filtered out and reduced to a comprehensible format. This is a task not simply of correlating a specific frequency to a particular rotating or vibrating part, but also of interpreting the time-related changes in vibration amplitude and frequency. Location of the accelerometer on a particular part will yield specific information. For example, to look solely at the imbalance of the main rotating assemblies, an accelerometer mounted on the bearing housing will present a frequency spectrum closely related to the shaft vibration [203]. One of the most important applications of vibration analysis is in detection of cracks specially in rotating shafts. Whilst rare, this type of defect may lead to long out-of-service periods, to heavy damages of the shaft-line, and, hence, to severe economic consequences. In order to insure the reliability of the machine and to avoid failures, the rotor should be removed and changed before the shaft strength is fully compromised. For this purpose, on-line VA is usually employed to identify rotor defects based on the vibration monitoring at the bearing probes. In this framework, the problem of rotating cracked shafts has been tackled with and investigated for a long time [216]. Nevertheless, due to the nature of the problem of crack detection in rotor shafts, the reliability and the accuracy of fault-identification algorithms become critical.

Thus, the use of numerical modeling methods integrates the poor operational feedback and, on the other hand, allows to study the dynamical effects of a crack on shaft lines and to verify the reliability of vibration patterns that are taken into consideration by the monitoring systems. Once the relevance of parameters used by monitoring systems is validated by the numerical predictions, the possibility to detect cracks during normal operating conditions may become an alternative and a less expensive strategy to the restricted operating and maintenance conditions [587].

Regarding the problem of rotating cracks, two main features have been recognized; first is the local flexibility introduced by the crack in relation to the affected shaft sections, and second is the opening–closing phenomenon of the crack during rotation, commonly called breathing mechanism. A propagating crack affecting a rotor opens and closes in time due to the rotation, the load and the vibration amplitudes. For horizontal rotors, the assumption of weight dominance is frequently made as the ratio between the lateral displacements due to the weight and the lateral displacements due to vibrations is about 20–50 in industrial rotating machines. The closure of cracks is so only determined by the rotation angle of the cracked section. For vertical rotors (e.g. large pump units), the encountered situation is quite different: the closure phenomenon is no longer driven by the angular position of the rotor but rather by the ratio of the contribution of axial force and bending moment to the local normal stress component. The effect of loads, such as the driving torque, the shear stress, the hydraulic and mechanic rotating unbalances on the impeller, on the breathing mechanism and the effects of operating conditions are no more negligible [160], [216], [533].

Likewise rotating shafts, bearings are one of the most important and frequently encountered components in rotating machinery. Fault identification of rolling element bearings using condition monitoring techniques has been the subject of extensive research for the last two decades. Vibration based condition monitoring has been the most used technique in this context. Ball bearing failures can be caused by several factors, such as incorrect design or installation, acid corrosion, poor lubrication and plastic deformation. During the bearing operation, wide band impulses are generated when rollers pass over the defect at a frequency determined by shaft speed, bearing geometry, and defect location (outer race, inner race, or roller). The difficulty in the detection of defects in bearings lies in the fact that, the signature of a defective bearing is spread across a wide frequency band and, hence, can be easily masked by noise and low frequency effects [465], [493].

To overcome this problem, both time and frequency domain methods have been developed. Time domain methods usually involve indices that are sensitive to impulsive oscillations, such as peak level, RMS value, crest factor analysis, kurtosis analysis, and shock pulse counting. These methods can yield satisfactory results if we select a frequency band where the ringing modes due to the defects are dominant. Alternatively, frequency domain techniques search for a train of ringings occurring at any of the characteristic defect frequencies. These techniques based on averaging technique [91], adaptive noise canceling [120], and high frequency resonance technique have been developed to improve signal-to-noise ratio for more effective detection of bearing local defects [489]. Besides, the technique of wavelet transform has been more and more utilized as a tool for machinery fault [644]. The advantage of Wavelet transform in comparison with commonly used Fourier transform is that it decomposes a signal into a series of short duration waves or local basis functions (i.e. wavelets) on the time axis which allows the analysis of fault-caused local phenomena in vibration signals [403], [644].

A Crack on a Rotating Machinery Part

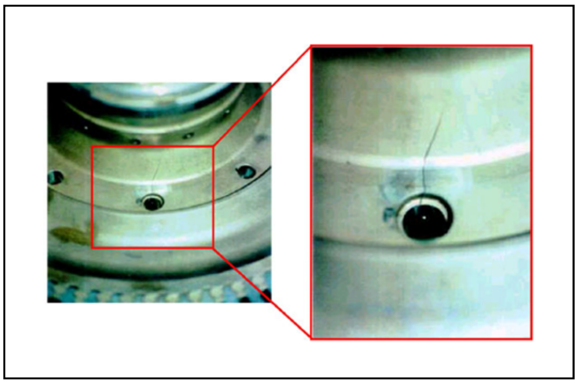


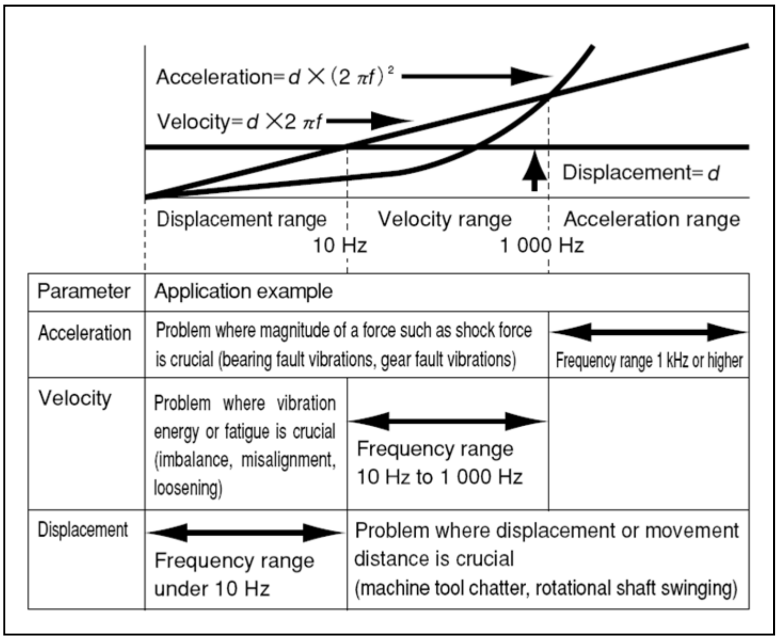
Figure 208 A crack on a rotating component that can be identified before its rupture by VA [WS93]

Another application of VA is in assessment of tool life and evaluation of tool wearing. Tool condition monitoring is necessary to obtain good quality product. Tool wear monitoring methods are classified into direct and indirect methods [218]. The direct method is implemented using optical devices to measure the geometry of the wear land. Indirect method is based on the acquisition of measured values of process variables (such as the change of size of the work piece, cutting force, temperature, vibration, spindle motor current, acoustic emission and surface roughness) and the relationship between tool wear and these values [380]. Among the process variables, vibration supplies the best information about tool condition. The advantages of vibration measurement include ease of implementation and the fact that no modifications to the machine tool or the work piece fixture are required [92]. Vibration monitoring is mainly used to detect tool condition, surface quality, dimensional deviations, and chatter phenomenon in machining applications. It is well known that vibration amplitude caused by interaction of a new tool and work piece is small compared to worn tool [466].

Regarding other applications, Kriel and Heyns have investigated the applicability of dynamic methods (forced-vibration analysis) in nondestructive damage detection for insulated piping [343]. In this particular case, ambient excitation due to flow was considered. The study examined the important structural modes through finite element analysis and verified these experimentally through frequency domain and time domain modal parameter estimation. The dynamic response to different forms of damage was investigated. Interestingly, it was determined that flow-induced vibration was sufficient to excite modes of interest and that the mode shapes were sensitive to uniform damage rather than localized corrosion, plus, temperature did not affect the results. Also, free- and forced-vibration techniques have been employed for crack detection in different structures from plates and beams to plant walls and even bridges that are considered as superstructures. Trendafilova and Manoach explained the limits of different vibration-based health monitoring methods and introduced two new methods and demonstrated them for a thin vibrating plate [625]. Loutridis et al. and Orhan have researched and represented their scientific and practical works about free- and forced-vibration analyses regarding the case of cracked beams [384], [466]. Burgueno et al. explained their specific empirical work about using VA for nondestructive evaluation of a bridge [100].

All in all, vibration monitoring and analysis can be used to discover and diagnose a wide variety of problems related to rotating equipment. Some generally accepted abnormal equipment conditions or faults, where this predictive maintenance tool can be of use, are: imbalance, misalignment, crack detection, resonance problems, mechanical looseness or weakness, eccentric rotors, rotor rub, sleeve-bearing problems, rolling element bearing problems, flow-induced vibration problems, gear and gearbox problems, belt drive problems. Each particular problem can be identified in certain frequency range which requires particular sensors to be examined; figure below provides the related information.

Problems, Vibration Parameter and Frequency Range



Parameter	Application example		
Acceleration	Problem where magnitude of a force such as shock force is crucial (bearing fault vibrations, gear fault vibrations)		Frequency range 1 kHz or higher
Velocity	Problem where vibration energy or fatigue is crucial (imbalance, misalignment, loosening)	Frequency range 10 Hz to 1 000 Hz	
Displacement	Frequency range under 10 Hz	Problem where displacement or movement distance is crucial (machine tool chatter, rotational shaft swinging)	

Figure 209 Relation between some particular problems, vibration parameters and frequency ranges [517]

6.14.4 Limitations and Pros

Although sometimes the fault appears to be clearly reflected in a machine's vibration signal, its characteristic features are usually hidden and, therefore, a sensitive technique for analysis of the fault signature is needed. In this sense, neural networks are a priceless pattern-recognition method in theory and in application. Because of this, models based on neural networks have been applied in recent years in the detection and diagnosis of rotating machinery.

Neural networks can be trained on measured response signals of healthy and damaged specimens to recognize the actual condition of the structure. The neural network architecture depends on which level of required identification. To detect the occurrence of damage, a neural network based on the different detection techniques can be used. In this framework, the objective is to monitor a sequence of patterns for a healthy structure under normal conditions. These patterns are used as both input and output to train the network. If a signal differs significantly from the herd, then the occurrence of this abnormality or deviation means that damage is probable [74], [472].

Briefly explained, detection of novelty (i.e. something new, original, and different that is interesting or exciting) or anomaly (i.e. something that deviates from the norm or from expectations - irregularity, or something strange and difficult to be identified or classified - peculiarity) can be used as a philosophy for damage detection purposes in machines or structures. According to this philosophy, if a new pattern of measured data in the machine or structure differs from previously measured patterns under normal conditions a clear symptom of damage appears, that is, novelty will indicate the presence of a fault [536], [668].

It is beneficial to keep in mind that vibration monitoring and analyzing of machinery and equipment to determine the presence of the reviewed problems are not a simple and easily performed procedure. Properly performed and evaluated vibration signature analysis requires highly trained and skillful individuals, knowledgeable in both the technology and the equipment being tested. Determination of some of the problems listed is less straightforward than other problems and may require many hours of experience by the technician to properly diagnosis the condition. However, today's technology advancement provides more and more automation and makes it easier for the users to benefit from vibration analysis as an effective condition monitoring technique [554].

Nonetheless, one of the advantages of vibration monitoring and analysis is that it can be effectively integrated or combined with other condition monitoring and nondestructive testing techniques [255]. An example can be the condition monitoring of bearings of rolling and rotating components. Vibration analysis is one of the best techniques available for detecting wear in rolling element bearings. High frequency vibration techniques such as demodulation can detect bearing problems in very early stages of wear and these defects can be easily tracked to failure using standard vibration spectral analysis. Ultrasound technology is extremely useful in managing a bearing lubrication regimen.

For example, over greasing can be avoided by listening to the bearing while greasing it using the acoustic lube method. Periodic monitoring of ultrasound levels lets one know when it is time to add additional grease to a bearing. Improper lubrication is a common cause of bearing wear and can seriously reduce the life of bearings. Therefore, ultrasound technology can help increase bearing life. Used together, ultrasound and vibration analysis complement each other in monitoring bearings; ultrasound as a preventative measure to ensure proper greasing and vibration analysis to detect initial stages of wear and track bearing defects until the bearing must be replaced.

On the whole, vibration analysis is widely used in predictive maintenance programs for pumps, motors, gearboxes, turbines, fans, and compressors, as well as all types of vehicles, heavy machinery, bridges, and civil engineering structures. Excessive vibration of equipment under load can be caused by wear, corrosion or even forces of nature, and is a major cause of equipment or structure failure. Hence, vibration analysis is an important and necessary maintenance endeavor in many industries. There are too many practical advantages associated with this condition monitoring technique that most of predictive maintenance program employ VA as one of the core focuses of their activities.

Table 58 Synopsis of vibration analysis

Pros	▪ Wide range of applications ▪ No part preparation required ▪ Visual, analog and digital output ▪ Sensitive to small discontinuities ▪ Possibility of real-time monitoring ▪ Fast, reliable and accurate output ▪ Wide range of materials can be inspected ▪ Chance of controlling of inaccessible zone ▪ Easily integrated with other CM/NDT methods ▪ Safe technique since no direct contact is involved ▪ Detects both surface and subsurface discontinuities ▪ Portable equipment is available for some applications ▪ Misalignment, imbalance and insecurity are readily detectable ▪ Detailed information can be provided to enable diagnosis of the fault type	
Limitations	▪ Sensitive to background/ambient noise ▪ Equipment and instruments are relatively expensive ▪ Complicated in analysis of on-stream monitoring data ▪ Highly skillful and well-trained operator/analyst required ▪ Test-derived data has to be compared with baseline data ▪ Speed variation of moving machinery elements affect test results ▪ Qualitative/quantitative interpretation of results needs advance knowledge ▪ Signal propagation from the source to the sensor is affected by structural resonances	
Equipment	▪ Handheld devices to highly automated stationary/remote systems having: transducers, data processors, signal analysis units and software	
Discontinuity types	▪ Crack ▪ Fatigue ▪ Corrosion ▪ Deformation ▪ Impact wear	▪ Stress crack ▪ Fatigue crack ▪ Corrosion crack ▪ Surface-breaking
Discontinuities size	▪ Very small discontinuities can be detected	
Relative inspection cost	▪ Equipment costs vary greatly according to their styles, types and capabilities. Transducers can cost under 50 €. The expected cost for vibration metering devices capable of defining magnitude with no analysis capability is approximately from 500 € to 750 €. Cost of a high-end vibration analyzer with software and all the accessories can exceed 15,000 €. A typical industrial site can expect to recover the cost of the high-end equipment investment within 2 years. Sites with a minimal number of rotating equipment, low-cost equipment installations, and/or no production related concerns may find it uneconomical to purchase such costly system. These facilities may be wise to establish an internal program of vibration monitoring using low-cost vibration-metering devices and then employ the services of an outside contractor to conduct periodic surveys. These services generally range in cost from 400 € to 700 € per day.	

6.15 Visual/Optical Inspection

By far, the most common NDT is visual and optical testing. In many instances, a trained inspector armed with simple tools, such as a flashlight and magnifying glass, can perform a very effective inspection. In quality control, as well as in maintenance operations, visual testing is the first line of defense. When deciding upon whether to use visual testing, it is important to understand its potential as well as its limitations. If the visual method is not sufficient for the problem at hand, more complex methods must be considered. Using the visual inspection method for enclosed systems can be challenging and possibly ineffective. To enable a technician or engineer to inspect these difficult-to-see areas, a device known as a borescope is often used. Borescopes are essentially miniaturized cameras that can be placed on the end of a fiber optic cable. The camera can then be inserted into regions that are obstructed from direct visual inspection, and the resulting images are viewed in real-time on a video screen by the inspector [412].

6.15.1 Conception

Visual inspection, aided or unaided, direct or remote, is a valuable nondestructive testing method and the oldest and most common form of the NDT in the manufacturing industries. Approximately 80 percent of all NDT procedures are accomplished by the direct visual methods. This inspection procedure may be greatly enhanced by the use of appropriate combinations of magnifying instruments, borescopes, light sources, video scanners, and other hi-tech devices. Visual inspection (VI) provides a means of detecting and examining a wide variety of component and material surface discontinuities, such as cracks, corrosion, contamination, surface finish, weld joints, solder connections, and adhesive disbonds. There exist two general methods of VI which are namely Eye-Mirror-Flashlight and borescopic inspection [16], [291]. These methods are reviewed and explained in the next section.

Nevertheless, it has to be highlighted that the full value of visual inspection can be realized only if records are kept of the discrepancies found on parts inspected. The size and shape of the discontinuity and its location on the part should be recorded along with other pertinent information, such as rework performed or disposition. The inclusion on a report of some visible record of the discontinuity makes the report more complete [580].

6.15.2 Tools and Techniques

The use of optical aids for visual inspection is beneficial and recommended. Optical aids magnify defects that cannot be seen by the unaided eye and also permit visual inspection in inaccessible areas. High-intensity light sources, magnifiers, borescopes, and television or video cameras can be used to enhance the detectability of surface-related defects.

The simple VI technique, eye-mirror-flashlight, is an important process in which the structure and machinery components such as cables, tubing, rods, pumps, actuators and etc. are frequently inspected. Visual inspection tools such as a powerful flashlight, a mirror with a ball joint and a 2 to 10 power magnifying glass are essential in the inspection process. It is vital to consider that flashlights used for machinery inspection should be appropriate for industrial use and, where applicable, approved by standard organizations as suitable for use in hazardous locations like flammable oil or fuel tanks.

Each flashlight manufacturer currently develops its tests and provides information on its products in its advertising literature. Therefore, when selecting a flashlight for use in visual inspection, it is sometimes difficult to directly compare products. The following characteristics should be considered when selecting a flashlight: foot-candle rating; explosive atmosphere rating; beam spread (adjustable, spot, or flood); efficiency (battery usage rate); brightness after extended use; and rechargeable or standard batteries. If possible, it would be best to take it apart and inspect for quality of construction and to actually use the flashlight like it would be used in the field. Inspection flashlights are available in several different bulb brightness levels which are as followings:

- Standard incandescent: for long battery life
- Krypton: for 70 percent more light than standard bulbs
- Halogen: for up to 100 percent more light than standard bulbs
- Xenon: for over 100 percent more light than standard bulbs

In addition to flashlights, inspection mirrors are used to view an area that is not in the normal line of sight. The mirror should be of the appropriate size to easily view the component, with the reflecting surface free of dirt, cracks, worn coating, etc., and a swivel joint tight enough to maintain its setting.

Simple magnifiers are also very useful in the VI process. A single converging lens, the simplest form of a microscope, is often referred to as a simple magnifier. Magnification of a single lens is determined by the equation $M=10/f$. In this equation, ‘M’ is the magnification, ‘f’ is the focal length of the lens in inches (1 inch = 2.54 cm), and ‘10’ is a constant that represents the average minimum distance at which objects can be distinctly seen by the unaided eye. Using the equation, a lens with a focal length of 5 inches has a magnification of 2, or is said to be a two-power lens [190].

Borescopes are long, tubular, precision optical instruments with built-in illumination designed for remote viewing of objects. In some cases, borescopes are needed because it is impossible to get close to the object that must be inspected, such as the internal parts of a motor. In other cases, it may be too dangerous to get close to the objects because of heat or other dangerous factors like existence of chemicals or radiation. They are typically used to inspect interiors of hydraulic cylinders and valves for pitting, scoring, porosity, and tool marks. Because of the variety of applications and inspection needs, borescopes are manufactured in rigid, extended, flexible, and micro designs. In general the diameter of a borescope determines the size of the minimum opening into which it can be inserted [190].

Typical Borescope Designs

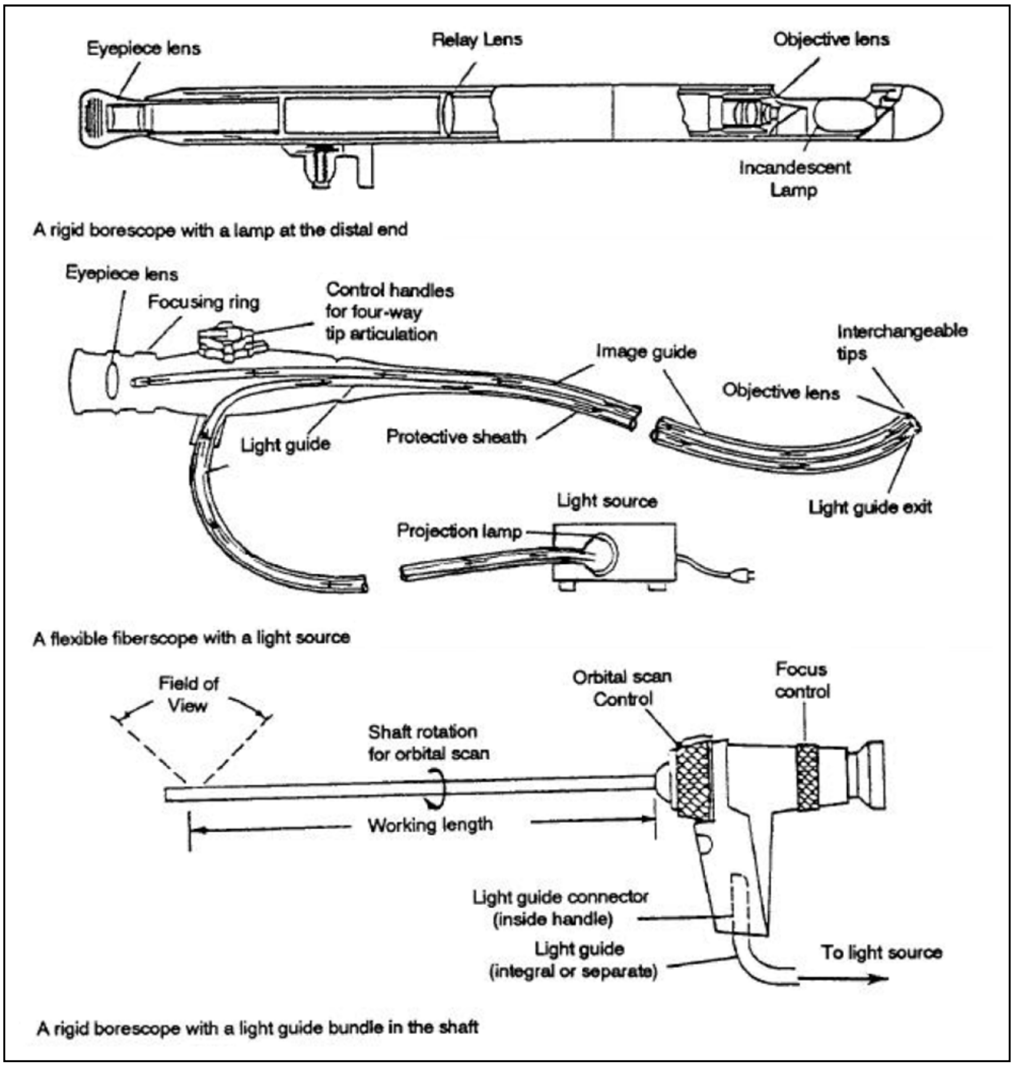


Figure 210 Two different types of borescopes, rigid and flexible borescopes, with their major components [190]

6.15.3 Use and Applicability

A visual examination of operational plant can be used to check for obvious problem areas, such as leaks, excess vibration or misalignment. On exposed metal surfaces it can also be used to check for corrosion. Plant coated with internal or external coverings, such as insulation, refractory protective linings and corrosion resistant linings, may be inspected visually if access permits. In such cases, a visual examination can be used to check that the protective layer has not separated and that it is free of breaks, holes and blisters. VI is also widely used for detecting and examining equipment surface cracks, which are particularly important because of their relationship to structural failures. It is frequently used to provide verification when defects are found initially using other NDT techniques [291].

It is central to carefully inspect the selected area for discontinuities using optical aids as required. An inspector normally should have available suitable measuring devices, a flashlight, and a mirror. When searching for surface cracks with a flashlight, one should direct the light beam at a 5 to 45 degree angle to the inspection surface, towards the face, and not to direct the light beam at such an angle that the reflected light beam shines directly into the eyes. It is also important to keep the eyes above the reflected light beam during the inspection and in order to determine the extent of any cracks found by directing the light beam at right angle. Use of a powerful magnifying glass is beneficial to confirm the existence of a suspected crack. If this is not adequate, one may use other NDT techniques, such as liquid penetrant, magnetic particle, or eddy current to verify cracks. VI facilitates the inspection of other surface discontinuities, such as: discoloration from overheating; buckled, bulging, or dented skin; cracked, chafed, split, or dented tubing; chafed electrical wiring; de-laminations of composites; and damaged protective finishes [190].

Use of Flashlight in Inspection of Cracks

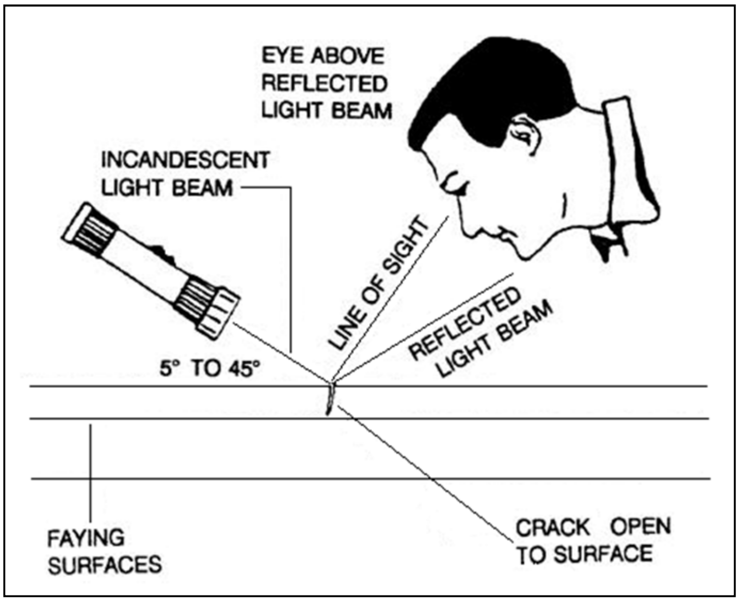


Figure 211 Proper use of flashlight in inspection of cracks and other surface flaws by naked eyes [190]

In addition to the mentioned uses of visual inspection of plant and machinery in industry, applications of VI aided by borescopes include:

- Inspecting steam generators
- Looking inside combustion boilers
- Inspecting the inside of molding rams
- Examining the interior of hydraulic cylinders
- Inspecting large gasoline and diesel engines
- Pinpointing weld imperfections inside of pipe
- Inspecting internal surface of pipes and tubes
- Inspecting the bores of shafts and large barrels

6.15.4 Limitations and Pros

Visual inspection is limited to exposed surfaces of a test object. Observable defects are normally limited to discoloration associated with fluids that cause corrosion or liquid-induced structural degradation of materials (e.g. shrinkage, crumbling and cracking). To be able to get whole use of this nondestructive testing method, it is essential to provide adequate lighting to illuminate the selected part or area under inspection. Moreover, personal comfort (temperature, humidity, etc.) of the inspector can be a factor in visual inspection reliability. Noise levels while conducting a visual inspection are important since excessive noise reduces concentration, creates tension, and prevents effective communication. It is clear that all these factors will increase the likelihood of errors.

Ease of access to the inspection area has been found to be of major importance in obtaining reliable visual inspection results. Access consists of the act of getting into an inspection position (primary access) and doing the visual inspection (secondary access). Poor access can affect the inspector's interpretation of discontinuities, decision making, motivation, and attitude.

Another factor affecting the results of VI is precleaning. It is highly important to clean the areas or surface of the parts to be inspected and to remove any contaminates that might hinder the discovery of existing surface indications. It has to be always kept in mind not to remove the protective finish from the part or area prior to inspection. Removal of the finish may be required at a later time if other NDTs are required to verify any visual indications of flaws that are found.

Table 59 Synopsis of visual/optical inspection

Pros	▪ Highly portable ▪ Minimum training ▪ Immediate results ▪ Minimum part preparation ▪ Large, medium and small size systems can be inspected ▪ Useful in preliminary examinations before application of other NDT
Limitations	▪ Require good lighting and eyesight ▪ Only surface discontinuities can be found ▪ Generally, only large discontinuities can be identified ▪ There is always possibility of misinterpretation of scratches
Equipment	▪ Very basic equipment such as mirrors and magnifiers ▪ Optical aids such as borescopes are optional except when checking-up internal surfaces
Discontinuity types	▪ Hole ▪ Crack ▪ Blister ▪ Fracture ▪ Corrosion ▪ Impact damage ▪ Surface-breaking discontinuities and deformation
Discontinuities size	▪ Down to 0.5 cm in general
Relative inspection cost	▪ It is relatively low but can be labor intensive ▪ Equipment costs vary from nothing to a modest price

6.16 Summary and Future Development Potentials

Until recent years, most of the maintenance investment decisions were used to be based on fulfilling technical specifications and on machinery purchase price. However, this has been changed taking into account additional criteria such as lowest possible operating costs, breakdown costs and maintenance costs which play increasingly important roles in the context of an integrated life cycle or the total cost of ownership, and also form decisive arguments in machine procurement. For instance, some examples in the automotive industry show that the repair and overhaul costs may exceed the investment costs of a machinery system after as little as five years of production. Preventive maintenance activities can only be beneficial if it they are enhanced with effective condition based maintenance efforts. An effective CBM program can only be implemented via efficient utilization of condition monitoring techniques and nondestructive tests.

Condition monitoring techniques and nondestructive tests, which are regarded as the extensions of human senses through the employment of advanced instrumentation, can make a noteworthy contribution to improving maintenance and reducing costs if they are utilized in the correct way and for proper applications. To ensure that a CMT or NDT brings with it the desired benefits, consolidated knowledge must be available. This is particularly essential for those tests and techniques which incorporate complex technologies and processes and embrace multifaceted applications. As intensively reviewed in this chapter, there are now many diverse CMTs and NDTs. In most cases the objectives of these tests and techniques fall into one of three categories as follows [99]:

- Measurement of physical or mechanical properties of materials in use or manufactured items
- Information on flaws, contaminations and wear in the material (e.g. machinery and equipment)
- Information about the condition of material which may have deteriorated or changed with time

Conversely, the misuse or improper application of a condition monitoring technique or a nondestructive test can have appalling outcomes. In case the test is not correctly conducted or if the interpretation and assessment of the test result are mistaken, reluctant results can occur. It is crucial that the most appropriate CMTs and NDTs are employed for each particular machinery type and anticipated problem in order to minimize the unwanted outcomes. In fact, CMTs and NDTs are priceless technologies that can provide useful information regarding the condition of the object under examination once all the important elements of the tests are considered, approved procedures are followed, and the examinations are conducted by qualified personnel. It is also central to underline that implementing these tests and techniques appropriately has a direct effect on environment-related issues as it reduces the number of catastrophic failures and defective components which have to be replaced and eventually recycled.

Each of the mentioned CMTs and NDTs through this chapter can be used to examine particular machinery objects and identify specific problems or discontinuities in definite materials. These factors restrain the applicability a test or technique. For instance, while penetrant testing and vibration analysis are capable of identifying surface-breaking cracks in metals, thermal inspection is not very effective. A general overview of such information is provided in the table below.

Table 60 Pertinence of different CMTs/NDTs for particular material and discontinuity types

Test Object Material	Discontinuity Type	Condition Monitoring Technique/Nondestructive Test													
		AT	EI	ET	LI	LT	MT	PT	RT	SA	TI	TT	UT	VA	VI
Metal (generic)	Porosity	-	X	X	-	-	-	X	X	-	-	-	X	-	-
	Corrosion pitting	-	-	X	X	-	-	X	X	X	-	-	X	-	-
	Stress corrosion cracking	-	X	-	X	-	-	X	-	X	-	-	-	X	-
	Welds - lack of penetration	-	-	X	-	-	-	-	X	-	-	-	X	-	-
Ferromagnetic Metal	Surface-breaking crack	X	X	X	X	X	X	X	X	X	-	-	X	X	X
	Non-surface-breaking crack	X	-	X	-	-	X	-	X	X	X	-	X	X	-
Non-ferromagnetic Metal	Surface-breaking crack	X	X	X	X	X	-	X	X	X	-	-	X	X	X
	Non-surface-breaking crack	X	-	X	-	-	-	-	X	X	X	-	X	X	-
Polymers	Cure	-	-	-	-	-	-	-	-	-	-	-	X	-	-
	Disbond	-	-	-	X	-	-	-	X	-	X	-	X	-	-
	Void/Porosity	-	X	-	X	-	-	X	X	-	X	-	X	-	-
Polymer-matrix Composite	Porosity	-	-	-	-	-	-	X	-	-	X	-	X	-	-
	Impact damage	X	-	-	X	-	-	-	X	X	X	-	X	-	X
	Delamination/Disbond	X	-	-	X	-	-	-	-	X	X	-	X	-	-
Ceramics	Density	-	-	-	-	-	-	-	X	-	-	-	X	-	-
	Void/Porosity	-	X	-	-	-	-	X	X	-	X	-	X	-	X
	Surface-breaking crack	-	X	-	X	X	-	X	X	X	X	-	X	X	X
	Non-surface-breaking crack	X	-	-	-	-	-	-	X	X	X	-	X	X	-

AT: Acoustic Emission Testing, **EI:** Electrical Inspection, **ET:** Electromagnetic Testing, **LI:** Laser Inspection, **LT:** Leak Testing, **MT:** Magnetic Particle Testing, **PT:** Penetrant Testing, **RT:** Radiographic Testing, **SA:** Stress Wave Analysis, **TI:** Thermal Inspection, **TT:** Tribological Testing, **UT:** Ultrasonic Testing, **VA:** Vibration Analysis, **VI:** Visual/Optical Inspection

Every condition monitoring technique or nondestructive test relies upon physical principles. Substantial improvements in their capability and accuracy result from improved processing and handling of data and from the power and speed of modern computers. Nevertheless, each test has limitations and by itself cannot a panacea. In most cases, a thorough examination requires a minimum of two methods: one for evaluation of the conditions that exist internally in the specimen and another method that would be more sensitive to assess the conditions at the surface of that specimen. It is essential that the applicability, detectability, advantages and disadvantages (ADAD) of every test be known prior to use. Hence, an overview of these factors is needed in order to be able to employ the right CMT/NDT for the proper inspection of particular items. To make this possible, a tabular ADAD overview of various NDTs and CMTs has been designed, developed, and provided in Appendix C.

This chapter provides a collection of fundamental expert knowledge about various condition monitoring techniques and nondestructive tests that are used for condition based maintenance of equipment and machinery in different manufacturing and processing industries. The knowledge has been also altered to intelligence as it is particularly formatted for ease of use and alleviated understanding. Nonetheless, a great potential for further development is to integrate the created expert-knowledge repository or knowledgebase, which is in the form of Word files, into smart software with multi-directional search possibilities. A searchable computerized knowledgebase in which, for example, a machinery component and a particular problem can be given and all alternative condition monitoring techniques and nondestructive tests utilized to predict that particular problem can be retrieved. Developing such software does not seem to be a big challenge as all the required expert knowledge about various CMTs/NDTs has been already gathered and structured in a way that in addition to their concepts, their applicability, detectability, advantages and disadvantages are clearly tailored and presented.

7 Decision Support Tools for the CBM Toolbox

The use of condition based maintenance and thus various condition monitoring techniques and nondestructive tests and in manufacturing plants is discussed by many scholars such as Mobley [440], Tsang [630], Waeyenbergh et al. [643], Saranga [538], Yang [673], Bengtsson [59], Castanier et al. [114], and De Silva [155]. Still, what is less focused on is how to choose the most appropriate CMT or NDT for a particular application. From time to time, the CMT/NDT method and procedure to be used for specific machinery part or component are specified in manufacturer's maintenance or overhaul manuals. Nevertheless, for many objects and equipment this does not hold true; hence, one has to have a broad knowledge of various methods and techniques which is almost impossible considering the breadth and depth of the related information. This was the main reason behind creating a CMT/NDT knowledgebase in which the applicability, detectability, advantages and disadvantages of a wide range of tests are on hand.

The CMT/NDT knowledgebase is able to provide its users with all alternative tests and techniques which can be utilized to predict and thus prevent a definite problem of a particular machinery component. These alternative tests are determined based on their applicability and detectability, denoting their pros and cons. Nonetheless, choosing the most appropriate CMT/NDT to be used for certain applications in a plant is not only related to the mentioned criteria but it is dependent on a long list of other factors. These range from economic considerations to safety and environmental issues. In order to have a systematic and standardized decision making process, two completely new tools have been pioneered. They ease this selection procedure while guarantee the quality and aptness of the resultant decision.

The first tool is a financial analysis contrivance which scrutinizes the economic aspects of all alternative condition monitoring technique and nondestructive tests derived from the CMT/NDT knowledgebase for a particular case and determines three financially essential elements associated with each test: cost effectiveness, return on investment, and payback period. The second tool is a selection matrix which takes into account usability, feasibility, efficacy, compatibility and safety factors associated with the CMTs/NDTs to be compared. The assessment outcome is a factor called as UFECS. Higher UFECS factor reflects higher suitability of a test to be used for a particular, predefined purpose.

7.1 Selection of CMTs/NDTs

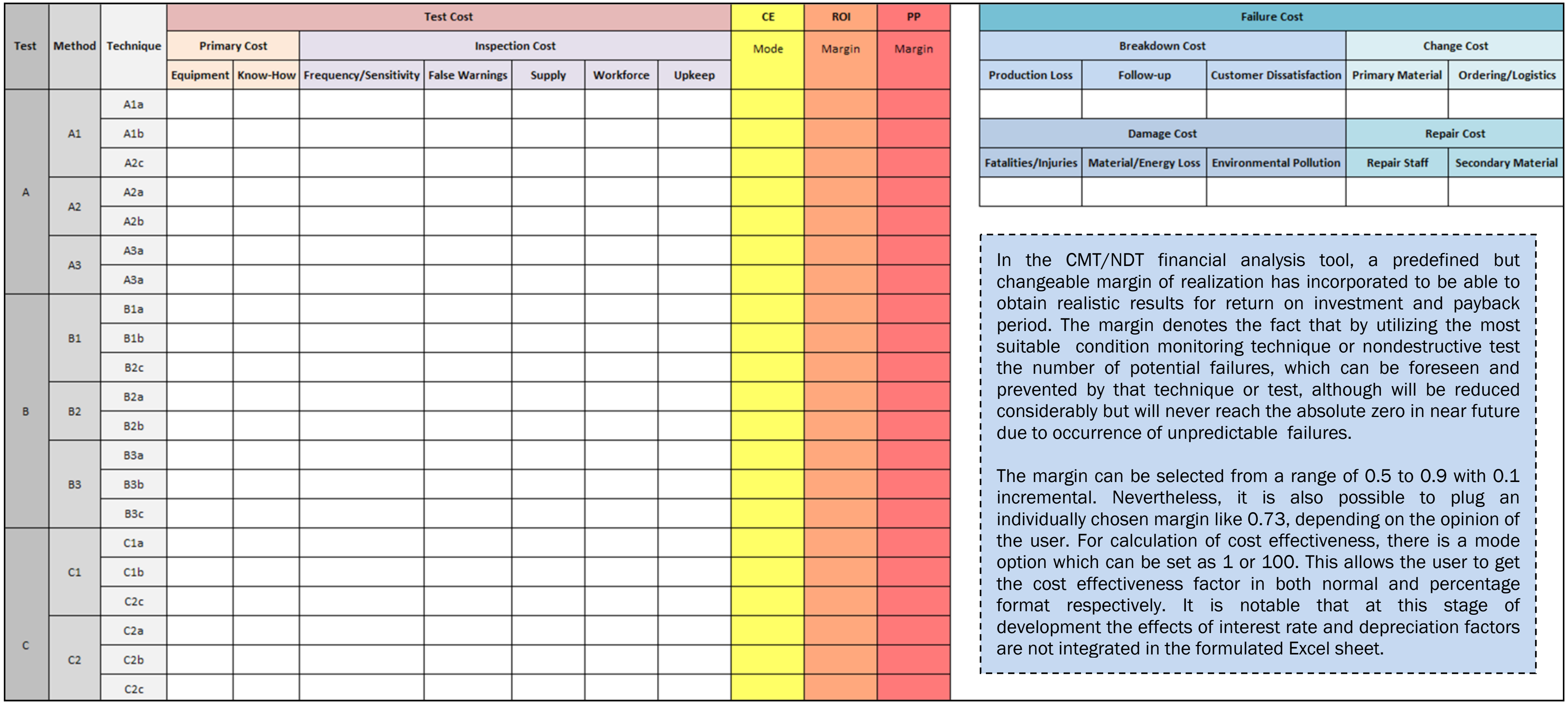
As mentioned before, the condition monitoring technique or nondestructive test to be used for inspection of a specific machinery part or component is sometimes specified in its manufacturer's maintenance or overhaul manual; however, most of the times, this is not the case. The appropriate CMT/NDT may consist of several separate inspections. An initial inspection may indicate the presence of a possible fault or defect, but other inspections may be required to confirm the original indication. Undertaking the correct CMT/NDT method selection requires an understanding of the basic principles, limitations, advantages and disadvantages of the available and suitable methods and an understanding of their comparative effectiveness and cost. There are some other factors affecting the type of inspection to be used which are the critical nature of the machinery part, material, size, shape, and weight of the part, the type of defect sought, maximum acceptable defect limits in size and distribution, possible locations and orientations of defects, part accessibility or portability, and the number of parts to be inspected or continuously monitored.

Another important parameter to be considered is the degree of inspection sensitivity which is required in selecting the CMT/NDT method. Critical parts that cannot withstand small defects and could cause catastrophic failure require use of the more sensitive CMT/NDT methods. On the other hand, less critical parts and general hardware generally require less-sensitive CMT/NDT methods. As the all the technical aspects of various condition monitoring techniques and nondestructive tests have been determined and highlighted in the CMT/NDT knowledgebase, there has always been a demand to figure out which test satisfies particular financial, business and industrial requirements which can vary from a definite payback period of the initial investment to certain compatibility constraints or safety obligations. To be able to respond to such needs, a financial analysis tool that evaluates a few economic factors and a selection matrix which takes into account some business-related issues have been developed. These decision support tools are introduced in the coming sections.

7.2 Financial Analysis Tool

Due to considerable initial investments (i.e. for hardware and software) and particular training and skill required, cost of running a condition monitoring technique or a nondestructive test is substantial; hence, there must be huge recompense to be gained in minimizing the amount of corrective or planned maintenance that is used to be performed and maximizing the CBM related activities. In addition, this must be balanced against the risks of machinery failure and the consequences of failure which are potentially very undesirable. For this reason, a tool has been developed to analyze each test or technique from financial perspective. In its framework, the tool which is in form of a smart Excel sheet calculates cost-effectiveness (CE), return on investment (ROI) and payback period (PP) of each individual test.

Structure of the CMT/NDT Financial Analysis Tool



Test	Method	Technique	Test Cost							CE	ROI	PP
			Primary Cost		Inspection Cost					Mode	Margin	Margin
			Equipment	Know-How	Frequency/Sensitivity	False Warnings	Supply	Workforce	Upkeep			
A	A1	A1a										
		A1b										
		A2c										
	A2	A2a										
		A2b										
	A3	A3a										
		A3a										
B	B1	B1a										
		B1b										
		B2c										
	B2	B2a										
		B2b										
	B3	B3a										
		B3b										
		B3c										
C	C1	C1a										
		C1b										
		C2c										
	C2	C2a										
		C2b										
		C2c										

Failure Cost				
Breakdown Cost			Change Cost	
Production Loss	Follow-up	Customer Dissatisfaction	Primary Material	Ordering/Logistics
Damage Cost			Repair Cost	
Fatalities/Injuries	Material/Energy Loss	Environmental Pollution	Repair Staff	Secondary Material

In the CMT/NDT financial analysis tool, a predefined but changeable margin of realization has incorporated to be able to obtain realistic results for return on investment and payback period. The margin denotes the fact that by utilizing the most suitable condition monitoring technique or nondestructive test the number of potential failures, which can be foreseen and prevented by that technique or test, although will be reduced considerably but will never reach the absolute zero in near future due to occurrence of unpredictable failures.

The margin can be selected from a range of 0.5 to 0.9 with 0.1 incremental. Nevertheless, it is also possible to plug an individually chosen margin like 0.73, depending on the opinion of the user. For calculation of cost effectiveness, there is a mode option which can be set as 1 or 100. This allows the user to get the cost effectiveness factor in both normal and percentage format respectively. It is notable that at this stage of development the effects of interest rate and depreciation factors are not integrated in the formulated Excel sheet.

Figure 212 A snapshot of the structure of the CMT/NDT financial analysis tool in Excel

Before considering the costs associated with putting a CMT or NDT into practice, the cost of failures which are supposed to be prevented by employment of a new test or technique has to be calculated. Here the most critical point to be considered is that, for example, if a test is utilized to prevent leaks in a plant only the failure costs which have been incurred due to leaks in a definite period of time have to be used for the upcoming calculations. When a failure occurs, it will inherently set off various costs which can be classified into four major categories: cost of breakdown (C_B), cost of machinery object(s) to be changed (C_C), cost of damage (C_D), and cost of repair (C_R).

$$C_F = C_B + C_C + C_D + C_R$$

Cost of breakdown can be further decomposed into three subcategories. Firstly, the cost associated with production loss during the breakdown (C_{PL}). This is the lost profit which could be obtained if the production ran continuously. Secondly, the cost related to delay or modification of planned production or other activities, known as the follow-up cost (C_{FU}). Thirdly, the cost coupled with customer dissatisfaction which can be further developed as asking for financial penalties, loss of future orders, or loss of positive reputation (C_{CD}). This is the most difficult segment to be calculated; however, over a definite period of time one can roughly estimate its value. For example, if a customer's order has been decreased by a value of 10,000€ in a year while receiving his complains about delayed shipments, and if there have been 10 breakdowns in the same year each of which happened manufacturing his goods, it is possible to logically infer that each breakdown cost 1000€ of customer dissatisfaction.

$$C_B = C_{PL} + C_{FU} + C_{CD}$$

Cost of broken machinery object(s) to be changed or simply cost of change is consisted of two elements. First is the direct cost of machinery object(s) itself which has to be replaced or repaired, which is known as the primary material cost (C_{PM}). Second is the cost associate with ordering, purchasing or commissioning (i.e. from a manufacturer, a third party, or own inventory), and related logistics of the spare part(s). This can be generally termed as cost of ordering and logistics (C_{OL}).

$$C_C = C_{PM} + C_{OL}$$

Cost of damage can be broken down into three distinct elements. First element is the cost associated with safety consequences which include any fatalities and injuries (i.e. both serious and minor) of the personnel due to the damage (C_{FI}). Second element is the cost related to possible material or energy loss due to the damage, which can be simply named as cost of loss (C_{LS}). This element is usually overlooked in industry but in fact it is of great importance. To have an impression, one can take into account how much money can be annually saved if a single air leak in a compressor is found and repaired. Third element is coupled with environmental consequences of the damage which embrace environmental pollution and deterioration (C_{EP}). Such incidents may oblige the company to undertake undesirable costly activities or even pay fines and extra charges set by the government. Evidently, C_{EP} is difficult to be quantified. However, it can be estimated by defining potential consequences that can result from a failure, and then, establishing relative severity of each consequence and assigning a value to each via referring to some benchmark or reference value used in similar companies.

$$C_D = C_{FI} + C_{LS} + C_{EP}$$

Cost of repair or corrective maintenance can be decomposed into two components. Firstly, the cost of repair staff who are employed or appointed to fix the broken machinery and damage (C_{RS}). Secondly, the cost associated with any secondary material (i.e. this can also include energy costs if they are considerable) used for the purpose of repair (C_{SM}). For example, material such as glue, screws, washers and etc. which are hold and used by maintenance technicians are classified in this category.

$$C_R = C_{RS} + C_{SM}$$

On the other hand, costs associated with a test are mainly divided into two major classifications, the primary costs (C_P) and secondary costs or the cost of inspection (C_I). Primary costs are the initial cost of purchasing necessary hardware and software to run the test (C_{EQ}) and cost of the personal training required or the know-how which has to be brought into plant to be able to implement the test (C_{KH}).

$$C_T = C_P + C_I \ | \ C_P = C_{EQ} + C_{KH}$$

Cost of inspection is relatively more complex to be calculated as it is consisted of various components. First is the cost of inspection itself in a definite time period which has two different aspects: the frequency of inspection and its degree of sensitivity (C_{FS}). To illustrate, one can consider a time period of one year as the reference. In this period, Test A has to be run once a month to be effectual and Test B has to be run twice a month for the same reason. If the estimated cost of inspecting with Test A for each session is 100€ and 70€ for Test B, then, the annual costs of running an inspection are 1200€ and 1680€ for Test A and Test B respectively. It is essential to underline that this cost involves the cost of material (e.g. oil, couplant, penetrant and etc.) and energy that are used every time a test is run. Besides, as the sensitivity requirement is set at a higher level, the related cost in a single session may increase due to longer inspection time and other factors. In case of continuous monitoring, such costs can only be calculated and consider per definite time periods such as a month, a quarter, or a year.

Second component is the cost increase due to possible false alarm or warnings (C_{FW}). Each CMT/NDT has a degree of reliability and during its implementation period it is possible to wrongly alarm a failure or problem. For continuous monitoring systems, this can be cost of stopping the production line and undertaking an inspection. For periodic tests, such a cost can be the cost of mistakenly changing a machinery component which can be used for longer time. Of course, before running a test it is almost impossible to have an accurate value for C_{FA}, but through consultation with experts or researches in similar industries, one can contemplate a rough estimation. Third is the cost of supply required to be available in the plant in order to run a test without any interruption or trouble (C_{SP}); this involves cost of spare parts or other material such as batteries which have to be kept in inventory. The next component is even more straightforward. It is the cost of the work force required in order to do an inspection (C_{WF}). Similarly, for continuous monitoring or inspection it is the cost of appointed work force (e.g. technician, analyst, etc.) in a definite time period. Eventually, the last component denotes the cost of maintenance or upkeep of the equipment, hardware and software required to undertake the inspection (C_{UK}).

$$C_I = C_{FS} + C_{FW} + C_{SP} + C_{WF} + C_{UK}$$

Regardless of if a test has to be undertaken periodically or if it is continuous monitoring technique, it is absolutely crucial to assign and calculate all of the failure and inspection costs for a same fixed period of time (i.e. preferably a year) and on the same logical basis. For instance, to decide whether or not it is economically feasible to run a leak testing (LT) program in a plant, one has to calculate the total failure cost which was come up by failures due to leakage in the last year, plus, the inspection cost that will be incurred if the LT program runs for a year. Having such a normalization and standardization done, the cost effectiveness, return on investment and payback period of utilizing a particular nondestructive test or a condition monitoring technique can be determined as presented below.

- **Cost Effectiveness** (CE) is used frequently in business planning and decision support. However, the term itself has no precise definition beyond the idea that both positive and negative financial impacts of an investment are going to be summarized and then weighed against each other. CE is a form of economic analysis that compares the relative expenditure (costs) and outcomes (effects) of an action. CE is often used where a full cost benefit analysis is inappropriate. Indeed, cost benefit analysis involves weighing the total expected costs against the total expected benefits of one or more actions in order to choose the best or most profitable option. However, in practice it is extremely difficult to consider all single costs and benefits and their monetary equivalents; that is why cost effectiveness can be used instead.

  In comparison with cost benefit analysis, CE uses a particular outcome measure that must be common among the investment cases being considered, its value is limited when they have some different outcomes. Although there is no generally used CE definition in literature but typically the CE is expressed in terms of a ratio where the numerator is a financial gain and the denominator is the cost of investment required to be able to achieve such financial gain. The result might just consider as a ratio or as a percentage. It is important to carefully consider what exactly CE means for the stakeholders. Within the borders of CMT/NDT financial analysis, CE is defined as the financial gain of employing a new CMT/NDT over the primary cost of the investment, that is, the initial cost of the equipment and know-how required to run a condition monitoring technique or a nondestructive test.

On the whole, if a new investment is dubbed cost effective and the term is used as its creators intended, it means that the investment is of a good value. However, if it does not have a positive CE, or if there are other opportunities with a higher CE, then the investment should be revoked.

$$CE = (C_F - C_I) / C_P$$

- **Return on Investment** (ROI) is a financial metric used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. To calculate ROI, the benefit or return of an investment is divided by the total cost of the investment; the result is usually expressed as a percentage. ROI is a very popular metric because of its versatility and simplicity. To illustrate, if an investment does not have a positive ROI, or if there are other opportunities with a higher ROI, then the investment should be revoked. It is said that other things being equal, the investment with the higher ROI is the better investment. ROI, however, says nothing about the risks in the investment. In complex business settings, it is not always easy to match specific returns (such as increased profits) with the specific costs that bring them. Business investments typically involve financial consequences extending several years or more. In such cases, the metric is meaningful only when the time period is clearly stated. Shorter or longer time periods may produce quite different ROI figures for the same investment. When financial impacts extend across several years, moreover, the analyst must decide whether to use discounted (net present value) figures or non-discounted values.

  Modifying the definition of ROI for this particular case, it can be described as: the financial gain of employing a new nondestructive test or condition monitoring technique over the total test cost as percentage. Here, the gain is defined as the failure cost minus the cost of inspection using that test. As it has been mentioned before the cost of failure and the test should have the same ground, that is, if one analyzes the possibility of employing leak testing, the cost of failures due to the leaks must only be taken into account. Another crucial point is that, whatever test and technique is employed to prevent a particular type of failure, it would barely be able to realize this goal to some extent. In other words, even after utilizing a new CMT or NDT in a plant, it can reduce the number of coupled failures by some percentage but never 100%. That is why a margin of realization is considered and multiplied by the gain to make it a reasonable value.

$$ROI = M(C_F - C_I) / C_T \times 100$$

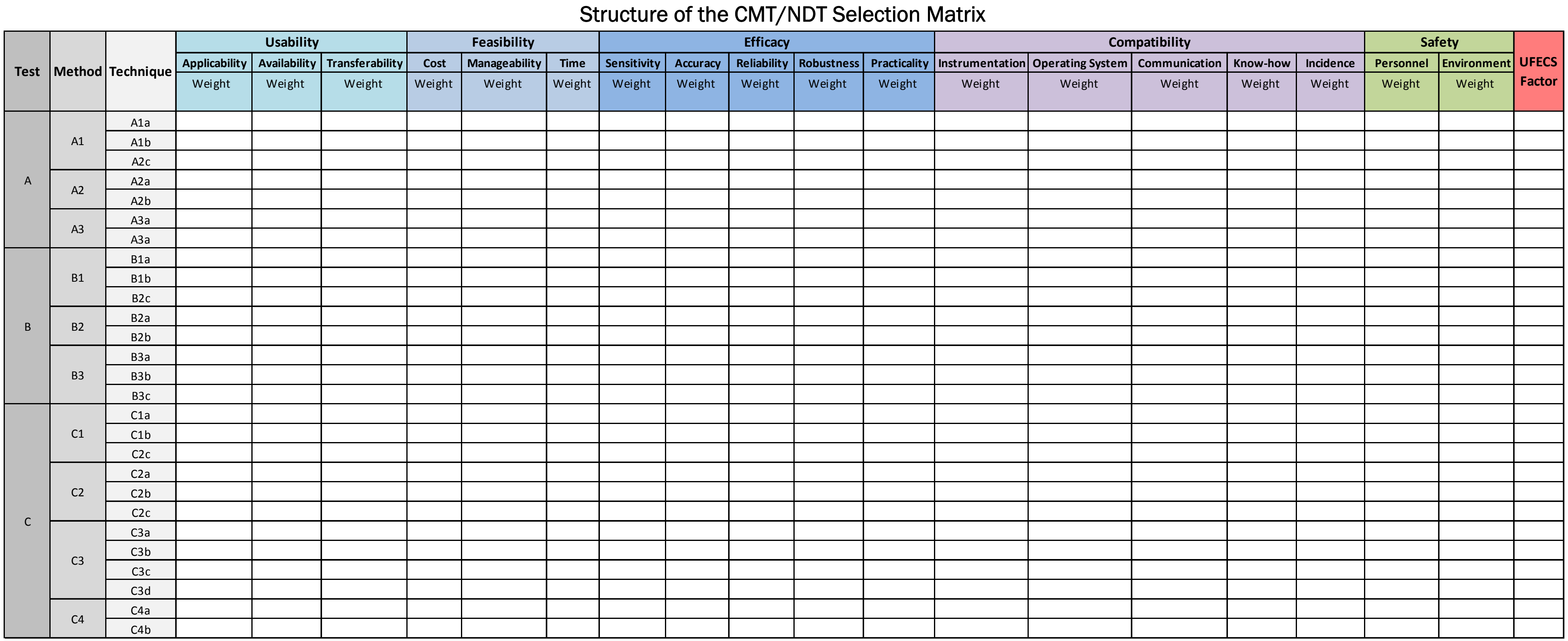
- **Payback Period** (PP) refers to the length of time required recovering the cost of an investment or, in other words, the period of time required for the return on an investment to repay the sum of the original investment. For example, a 1000€ investment which returned 500€ per year would have a two year payback period. It intuitively measures how long something takes to pay for itself. Other things being equal, shorter payback periods are obviously preferable to longer payback periods. Payback period is widely used due to its ease of use despite recognized limitations. It is important to consider that PP ignores any benefits that occur after the payback period, and so it does not measure possible total gains or incomes. Payback period as a tool of analysis is often used because it is easy to apply and easy to understand for most individuals, regardless of academic training or field of endeavor. However, it is also considered a method of analysis with serious limitations and qualifications for its use, because it does not properly account for the time value of money, risk, financing or other important considerations such as the opportunity cost.

  Altering the definition of PP for this particular case, it can be defined as: the primary cost of employing a new nondestructive test or condition monitoring technique over the resultant gain or financial benefit. The gain is again the failure cost minus the cost of inspection using that test. All the critical points which have been previously taken into account hold for calculation of payback period as well. Here, a margin of realization is used to provide more realistic gain or financial benefit figures. The reason, as previously explained, is that there is no NDT or CMT which is able to entirely prevent occurrence of particular failures.

$$PP = C_P / M(C_F - C_I)$$

7.3 CMT/NDT Selection Matrix

The CMT/NDT selection matrix is a valuable tool designed to standardize and ease the decision making process in selecting the most appropriate CMT/NDT for a particular case in a plant. This tool, which has been developed as smart Excel sheet, evaluates the overall effect of different criteria that are central to decide on the most suitable test or technique to be used to prevent a certain type of problem.



Structure of the CMT/NDT Selection Matrix

Test	Method	Technique	Usability			Feasibility			Efficacy					Compatibility					Safety		UFECS Factor
			Applicability	Availability	Transferability	Cost	Manageability	Time	Sensitivity	Accuracy	Reliability	Robustness	Practicality	Instrumentation	Operating System	Communication	Know-how	Incidence	Personnel	Environment	
			Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	
A	A1	A1a																			
		A1b																			
		A2c																			
	A2	A2a																			
		A2b																			
	A3	A3a																			
		A3a																			
B	B1	B1a																			
		B1b																			
		B2c																			
	B2	B2a																			
		B2b																			
	B3	B3a																			
		B3b																			
		B3c																			
C	C1	C1a																			
		C1b																			
		C2c																			
	C2	C2a																			
		C2b																			
		C2c																			
	C3	C3a																			
		C3b																			
		C3c																			
		C3d																			
	C4	C4a																			
		C4b																			

Figure 213 A snapshot of the structure of the CMT/NDT selection matrix in Excel

The CMT/NDT selection matrix takes into account the degree of usability, feasibility, efficacy, compatibility and safety of the condition monitoring techniques and nondestructive tests to be compared through allocating some numbers representing the status of all these elements. This is done via a ranking system from 1 to 5, which designates the qualitative value of the mentioned factors; here rank 1 denotes the worst and rank 5 reflects the best situation or effect. Each factor is then multiplied by a weight that signifies how important this specific factor is for the company itself. Having all the factors normalized, the assessment results in an overall evaluation factor called UFECS. Higher UFECS factor reflects higher suitability of a nondestructive test or a condition monitoring technique to be used for a particular purpose in the plant.

Not to leave the factors used for evaluation blurred and indistinct, the author defines and describes each and every of the major and minor factors utilized. It is central to just consider these factors within their defined frames while undertaking the evaluation and using the selection matrix. The second crucial issue to express is that although the ranks are given titles, the definition and extent of each rank has to be set and defined for every particular test and every particular company. For instance, while sensitivity for leak testing can be defined by the number of molecules fluid per cubic centimeter the test identifies, the sensitivity for radiographic testing is associated with the characteristics of the cracks it is able to determine. The same way, while for a small company a test's cost at a scale of 50,000€ can be considered as very high, the same number for a large size firm can be assessed as low or tolerable.

Below, all of the major and minor factors, which are incorporated for evaluation and comparison of the suitability of different CMTs/NDTs in the selection matrix, are described, defined and explained.

1. **Usability:** It denotes the capability of a nondestructive test or condition monitoring technique of being used. In other words, it signifies level of fitness of test for use. Usability is evaluated in terms of applicability, availability and transferability.

- ***Applicability:*** The applicability criterion simply serves to ensure that any test selected to be used on a machinery system for monitoring or detecting a particular discontinuity or problem has been designed and can be effectively utilized for that intended use.

  Level 5: Extremely Applicable, *Level 4:* Highly Applicable, *Level 3:* Moderately Applicable, *Level 2:* Applicable, *Level 1:* Poorly Applicable

- ***Availability:*** It refers to the commercial availability of a test and its associated requirements (e.g. hardware, software, and training).

  Level 5: Vastly Available, *Level 4:* Easily Available, *Level 3:* Available, *Level 2:* Barely Available, *Level 1:* Almost Unavailable

- ***Transferability:*** This criterion requires a close examination of expected operating conditions. Particular operation conditions such as lack of space, time and skillful operators, or safety and security considerations associated with the operation activities are typical issues that may preclude the installation or limit the effectiveness of a certain test. Besides, regional considerations (i.e. environmental conditions and particular rules and regulations) should also be used in determining whether a specific test is transferable or not. A sound understanding of existing and expected operating conditions together with the test limitations is necessary for the successful implementation of any test. The necessary operating conditions and the situations which should be avoided are usually known for each test.

  Level 5: Easily Transferable *Level 4:* Transferable *Level 3:* Moderately Transferable *Level 2:* Barely Transferable *Level 1:* Not Transferable

2. **Feasibility:** This refers to the degree to which something can be achieved, carried out, or put into effect. Feasibility is usually defined with respect to the cost, manageability and time required to achieve or realize a certain objective. Among a particular group of alternatives, any choice which can be realized or taken in with lower cost, lower degree of manageability and in a shorter time has a higher feasibility.

- *Cost:* Usually, vendors are extremely reluctant to provide absolute hardware and software costs for nondestructive testing or condition monitoring systems because there is no way to accurately extrapolate the numbers without getting in the installation or even implication phase. They also indicate that there is a great deal more to the cost of owning a testing system than the bare bones system price (e.g. the relative cost of instruments, maintenance or life cycle costs, and costs associated system updates). Besides, the real and potential costs incurred for each incorrect alarm, missed alarm, late alarm, and/or any other deviation from ideal performance may also be taken into account. In short, the true cost associated with a newly adopted test must include an institutional and management cost. Prior to installation this cost is more difficult to quantify than the purchase cost of the test itself, and increases with an operator's increased commitment to attain a higher level of sensitivity. For these reasons and unless the vendors provide actual numbers, the costs associated with each test are discussed only qualitatively or in a range and just of those associated with hardware, software and installation. Nevertheless, there are often tradeoffs between the price of a test and its performance. Naturally, highly effective systems (sensitive, accurate, reliable, and robust) ultimately will cost more to implement and maintain. Of course, it is up to the company to establish machinery specific performance standards and weigh the costs and benefits of a test.

  Level 5: Very Low *Level 4:* Relatively Low *Level 3:* Bearable *Level 2:* High *Level 1:* Very High

- *Manageability:* This criterion underpins the extent to which a NDT or CMT is easy to deal with. In other words, it signifies the difficulty or simplicity level at which a test can be handled or controlled. Indeed, higher level of manageability indicates a nondestructive test or a condition monitoring technique is more tractable.

  Level 5: Easily Manageable *Level 4:* Manageable *Level 3:* Fairly Manageable *Level 2:* Hardly Manageable *Level 1:* Not Manageable

- *Time:* The time length required for a test to be undertaken is of considerable importance especially from a financial perspective; shorter inspection time inherently connotes lower associated costs. For a continuous monitoring technique this criterion can be considered as the start-up time or the time needed to receive first results after turning the system on.

  Level 5: Very Short *Level 4:* Short *Level 3:* Moderate *Level 2:* Long *Level 1:* Very Long

3. **Efficacy:** Efficacy is defined as the power or capacity to produce a desired effect, or in other words, prospective effectiveness. In UFECS framework, efficacy deals primarily with the performance related aspects of a nondestructive test or a condition monitoring technique and is evaluated in terms of sensitivity, accuracy, reliability, and robustness in addition to considering its practicality level which represents the quality or state of being practical. It is essential to highlight that focus on achieving ideal performance in one criterion, e.g. sensitivity, usually results in some degradation of the other criteria. To exemplify this, consider the following hypothetical tests:

   Test-1: This test incorporates a sensitive technique. The test is normally very reliable, but will frequently generate alarms during regular inspections or normal operations.

   Test-2: This test incorporates an alternative technique which is somewhat less sensitive than that of Test-1, but generates only a fraction of the alarms.

   Test-3: This test incorporates the same sensitive technique as Test-1, but inhibits some problems during normal operations that can cause it to generate alarms.

   Test-4: This test normally incorporates the same sensitive technique as Test-1, but switches to the less sensitive technique of Test-2 when it experiences conditions that engender alarms.

   To facilitate maintaining a high level of sensitivity, Test-1 forfeits a degree of reliability, whereas Test-2 forgoes some degree of sensitivity in order to achieve a high level of reliability. Via disabling the detection capability under certain conditions, Test-3 sacrifices a degree of robustness in order to achieve higher levels of sensitivity and reliability.

Conversely, Test-4 represents and attempts to achieve more robustness at the expense of sensitivity and reliability. Certainly, the artful tactic is to manage a satisfactory tradeoff between accuracy, reliability robustness, and sensitivity by understanding the specific operating conditions of a machine or equipment and the stakeholders' expectations. Indeed, the selection of a test to be used for maintenance purposes depends upon the performance requirements specific to the company.

- *Sensitivity:* Sensitivity is defined as the composite measure of the size of discontinuity or severity of a problem that a test is capable of detecting, and the time required for it to generate an alarm in the event that a discontinuity of that size or a problem of that severity should occur. The relationship between discontinuity size or problem severity and the response time is dependent upon the nature of the test itself. Some tests manifest a strong correlation between discontinuity size or problem severity and response time, while with others response time is largely independent of the size or severity. In general, excluding a few exceptions, there is no test that tends to detect small discontinuities more quickly than large ones. Sensitivity can be evaluated based on the extent a condition monitoring technique or a nondestructive test has the continuous capability to detect a discontinuity or problem equal to not more than some fixed limits. In terms of response time, the test must be capable of detecting discontinuities or problems promptly.

  Level 5: Extremely Sensitive *Level 4:* Highly Sensitive *Level 3:* Sensitive *Level 2:* Poorly Sensitive *Level 1:* Insensitive

- *Accuracy:* Accuracy is a measure of test performance related to estimation of predefined discontinuity or problem parameters (e.g. crack location, crack growth, temperature variation, leakage rate, volume lost and etc.). A test that estimates these parameters within an acceptable degree of tolerance, as predefined by the standards, manufacturers' manuals or the company's guidelines, is considered to be accurate. Sometimes a test gets use of various instrumentations and different devices. The accuracy of these systems is evaluated in terms of the accuracy, repeatability, and precision of the stated or estimated values in their brochures or practical knowledge of technicians who are experienced and previously worked with these instrumentations and devices.

  Instrument accuracy represents the measurement performance of the instrument relative to that of an ideal device. Repeatability is a measure of the instrument's ability to consistently return the same reading for a given set of conditions. Precision is a measure of the smallest change that can be seen in the output of the instrument. For example, a test's accuracy can be discussed in terms of its capability of to locate a crack of particular size within a certain radius of an indicating sensor.

  Level 5: Extremely Accurate *Level 4:* Highly Accurate *Level 3:* Accurate *Level 2:* Poorly Accurate *Level 1:* Inaccurate

- *Reliability:* Reliability is a measure of the ability of a test to deliver correct verdicts about the possible existence of a discontinuity or problem in/on a machine or equipment. It is directly related to the probability of detecting a discontinuity or problem, given that it does in fact exist, and the probability of incorrect decrees, given that no symptom has occurred. A test that incorrectly decrees discontinuities or problems is considered to be less reliable; however, if the test has the capability to utilize additional information to disqualify, limit, or inhibit an alarm, a high rate of such decrees may be considered less significant.

  Reliability pertains only to hardware and software used by a test, not the controlling system, secondary instrumentation, communication equipment, or any other factor beyond the control of the test itself. Reliability can be managed through controller response and established procedures; however, unless the test automatically adjusts to decision thresholds, these procedures cannot be used to discriminate between systems. Hence, the reliability of a test can be assessed in terms of the frequency and cause of reported false alarms on operating systems, and the ability of the test to automatically evaluate operating conditions and adjust alarms thresholds.

  Level 5: Extremely Reliable *Level 4:* Highly Reliable *Level 3:* Reliable *Level 2:* Fairly Reliable *Level 1:* Unreliable

- *Robustness:* Robustness is a measure of a test's ability to continue to function and provide useful information, even under changing operation conditions. A test is considered robust if it continues to perform its principle functions under less than ideal conditions. Robustness can be evaluated in terms of the capability of the test to distinguish between normal transient operating conditions and real problematic events, and the ability to automatically make temporary system adjustments or disable certain functions as needed. Robustness can also be evaluated in terms of the ability of a test to continue its task in the event that an associate instrument or device is partially damaged, completely lost or goes off line.

  Level 5: Tremendously Robust *Level 4:* Strongly Robust *Level 3:* Robust *Level 2:* Weakly Robust *Level 1:* Not Robust

- *Practicality:* The evaluation of a test's actual field performance (in contrast with its laboratory performance) is essential to substantiate vendor claims of system accuracy, reliability, and robustness and sensitivity. Industry references provided by the vendors can be contacted and the widely known and accepted reputations can be considered to verify and comment on the field performance of a particular test.

  Level 5: Extremely Practical *Level 4:* Highly Practical *Level 3:* Fairly Practical *Level 2:* Poorly Practical *Level 1:* Impractical

4. Compatibility: In technological terminology, compatibility refers to the ability to be used together with or substituted for another piece of hardware or software, or the consistency with the existing ones. In fact, The operating requirements of each condition monitoring technique or nondestructive test, including instrumentation, communications, sampling frequency, and operator or controller training are presented under this criterion to enable the potential user to further evaluate whether a test is compatible with currently used systems in a plant or not.

- *Instrumentation:* Instrumentation requirements for the installation and operation of a nondestructive test or a condition monitoring technique at a plant include all hardware and peripherals that may be required or are optional that may enhance the performance of the test. It is impractical and more costly if none of the instrumentation required to run a test is compatible with the current systems used in the plant (e.g. one may think of specific computer ports to which the cables from various sensors would be connected).

  Level 5: Extremely Compatible *Level 4:* Highly Compatible *Level 3:* Fairly Compatible *Level 2:* Poorly Compatible *Level 1:* Not Compatible

- *Operating System:* Operating systems denote how the systems electronics interface, i.e. via which software. Whether or not any operating system used by the test equipment is completely compliant with the one used by the systems in the plant is crucial. For instance, if the computer system of plant operates with Windows Vista and Personal Digital Assistants (PDAs) used to collect data from sensors operates with Windows XP, they are considered to be highly compliant; however, if the system in a plant runs on Linux they are considered to be poorly compliant.

  Level 5: Extremely Compliant *Level 4:* Highly Compliant *Level 3:* Fairly Compliant *Level 2:* Poorly Compliant *Level 1:* Not Compliant

- *Communication:* Communication requirements for each system vary from none to systems that have the ability to be accessed remotely or are incorporated into the onsite computer network. The extent to which the communication means of the testing system and the plant's communication system match each other plays an important role. For example, if the CMT/NDT system uses a wireless system and there are already wireless routers and receivers available in the plant, the communication means of the NDT or CMT is considered to be highly adjustable.

  Level 5: Extremely Adjustable *Level 4:* Highly Adjustable *Level 3:* Fairly Adjustable *Level 2:* Poorly Adjustable *Level 1:* Not Adjustable

- *Know-how:* This criterion is coupled with the time and cost of test operator training. Many systems providers will come to the site and provide hands-on training, while others require training at their headquarters. There are several systems that boast that their system is so simple and easy to operate that no or minimal training is required.

  Level 5: No Training Required *Level 4:* Minimal Training Required *Level 3:* Moderate Training Required *Level 2:* Intensive Training Required *Level 1:* Long and Intensive Training Required

- *Incidence:* System design regarding testing frequency varies. For systems categorized as continuously monitoring testing frequency may be cycled. Other systems are automatic testers and will take advantage of system "down times" or quiet times when the system is not in service. Systems that are not in the first two categories and are not continuous or considered automatic are the ones that are incorporated into the regularly scheduled maintenance program.

  Level 5: Infrequent / Autonomously Online *Level 4:* Seldom / Semi-Autonomously Online *Level 3:* Fairly Frequent / Manually Online *Level 2:* Frequent / Partially Online *Level 1:* Exceedingly Frequent / Not Online

5. Safety: It is generally interpreted as implying a real and significant impact on risk of death, injury or damage to property.

- *Personnel:* This criterion is linked with the personnel's condition of being protected against physical and psychological consequences of undertaking a nondestructive test or condition monitoring technique, or a related which could be considered non-desirable. This can take the form of being protected from the event or from exposure to something that causes health losses.

  Level 5: Safe *Level 4:* Relatively Safe *Level 3:* Tolerable *Level 2:* Hazardous - With Warning *Level 1:* Hazardous - Without Warning

- *Environment:* Environmental impacts can be assessed under various standards and regulations by determining whether the environmental impacts of each alternative test, such as air, land, water, energy, and other requirements, may offset any anticipated environmental benefits. Nondestructive tests and condition monitoring techniques with internally installed small devices do not typically represent a significant change to the surrounding environment. However, tests and techniques with externally installed or used systems may bring with or necessitate disturbances to the environment surrounding the machinery to be tested.

  Level 5: No Impact *Level 4:* Low Impact *Level 3:* Manageable *Level 2:* Hazardous - With Warning *Level 1:* Hazardous - Without Warning

7.4 Summary and Future Development Potentials

To be able to choose among the alternative condition monitoring techniques and nondestructive tests which turned to be possible solutions for condition based maintenance of a specific machinery component with a particular failure mode, two decision support tools have been developed. These are a CMT/NDT financial tool and a selection matrix. The former tool analyzes the economic aspects of all alternative CMTs and NDTs to be compared and provide their cost effectiveness, return on investment, and payback period. The later evaluates all alternative CMTs and NDTs with respect to their usability, feasibility, efficacy, compatibility and safety factors. The outcome is a factor called as UFECS. Higher UFECS factor reflects higher suitability of a CMT/NDT to be used for a particular case.

The future development potentials for both tools, specially the CMT/NDT financial analysis tool, are considerable. Both tools can be integrated into software which is given all necessary data, or retrieves them from a plant's information system, calculates and provides the factors such as CE, ROI, PP and UFECS. Besides, in addition to the used three, other financial factors can be integrated in the CMT/NDT financial analysis tool. The current formulae can be updated and advanced taking into account some other finance and accounting concepts such as interest rates and depreciation factors in order to achieve more realistic and reliable results.

8 Object Based Problem and Cause Analysis for the CBM Toolbox

Object based problem and cause analysis (OBPCA) is another major tool of the CBM toolbox. In this analysis, for a particular object (e.g. a bearing) or machinery (e.g. a pump), all possible problems are identified, the most common problems are chosen, the probable causes of these problems are determined, and eventually the problems and causes of these problems are correlated in a specific format which is compact but easily understandable. This can be realized in the form of a specially formatted table or a fishbone diagram. Though, the tabular format seems to be more comprehendible providing well-structured extensive information in a simpler visual manner in comparison with the fishbone diagram with several forks.

Such a tabulated list of problems and their correlated causes is inclusively forged based on the work of Hattangadi [256], Marquez and Herguedas [406], Mobley [440], [442], [443], Mobley et al. [444], Smith and Mobley [574], [575], and Sachs [534], by adjoining, moderating or modifying some information founded on academic literature surveys, review of technical reports in different industries, retrieving failure history data from the information system of TRW Schalke and talks with experts. Nevertheless, such tables need to be frequently reviewed and updated based on the newer plant failure data and the upcoming international publications in the field of machinery failure analysis.

There have been many motives behind developing such a tool and integrating it in the CBM toolbox. One of the critical reasons is the improperly made problem and cause lists in the information systems of different plants. The importance of such lists is usually overlooked and when recognized, there is usually no concrete solution for optimizing these lists. It has to be noted that these are the lists, using the information of which operators inform maintenance department of a failure occurrence and maintenance technicians comment on the quality of this failure after repair.

In other words, the tabulated information are the foundation of all generated and accumulated failure data in the information system; the data based on which a statistical failure analysis can be undertaken and central maintenance or spare part/inventory related decisions may be made. OBPCA, if undertaken for majority of machines and machine elements in a plant, can be utilized to determine the most common problems and problem-causes and hence develop the optimal problem and cause list in the information systems.

Another reason behind undertaking object based problem and cause analysis, and developing OBPCA tables is that even in the presence of optimal problem and cause lists in the information system it cannot be expected from each and every technician to recall all possible problems and causes associated with a particular machinery object. If there is a problem or cause which is not in those common lists (i.e. which are intentionally not very detailed, otherwise extinguish their practicality) the technician should first be able to identify it and second report it in a proper technical language.

Obviously, this is not always possible unless there is a certain tool which facilitates the technician with providing high quality and reliable information in a common language which is easily understandable by everyone in the plant. At any machinery failure occurrence, a previously undertaken object based problem and cause analysis can be used as a standard catalog or reference by the technicians to provide a flawless feedback containing reliable information about the occurred problem and its possible cause(s). Indeed, OBPCA tables eventually brought about entering higher quality information in the plant's information system and thus more reliable analysis which are based on such information.

On the whole, having higher quality and more reliable data entering the plant's information system, the information which is provided by statistical failure analysis will definitely have higher quality and reliability as well. The decisions which are taken based on such information are more consistent and trustworthy. Consequently, the CMT/NDT knowledgebase can be more effectively used to identify the most appropriate alternative solutions. And eventually, the machinery problems can be more proficiently predicted and prevented. As the ultimate outcome, there will be less and less number of failures in the plant (i.e. zero failure concept) and the overall operation and maintenance costs will be considerably reduced. In this chapter, OBPCA tables for bearings, compressors, control valves, conveyors, fans, gear systems and pumps along with valuable information about their characteristics and maintenance are presented.

8.1 Bearings

Bearing is a machine element allowing constrained relative motion between two or more parts, typically rotation or linear movement. It supports other machine elements such as shafts that rotate or slide in or on it [443]. In order to bear the extremely high fatigue stresses and provide relatively long life, the bearings are made of very hard steel with some alloy variations. The normal maximum operating temperatures at which typical bearing materials can be run for long time without hindering their reliability is about 120°C. Their strengths are not affected for about another 50°C; however, bearing operating stresses generate additional heat and thus it is necessary to leave a reasonable margin of safety. Nevertheless, there are special bearings which withstand temperatures up to 310°C for lightly loaded applications. Nowadays, several coatings are used to improve bearings life in wet, corrosive, and contaminated operations [534]. In general, bearings can be classified into two very broad groups: plain and rolling bearings.

8.1.1 Plain Bearing

Plain bearings, also known as plane or fluid-film bearings, are available in a wide range of designs and maybe self-contained units or built into a machine assembly. They are indeed the simplest type of bearing comprising of just a bearing surface and no rolling elements but a journal which slides over the bearing surface. Generally, plain bearings are less expensive than rolling bearings. They are also compact, lightweight, and have a high load-carrying capacity. Plain bearings must be made from a material that is durable, low friction, low wear to the bearing and shaft, and resistant to corrosion and elevated temperatures.

Conventionally, the bearing is made up of at least two elements, one of which is soft and the other is hard. The hard element supports the load while the soft element supports the hard one. In general, the harder the surfaces in contact the lower the coefficient of friction and the greater the pressure required for the two to seize [440]. A common plain bearing design is to use a hardened and polished steel shaft and a soft bronze journal or bushing. In such designs the softer bronze portion can be allowed to wear away, to be periodically renewed. It is notable that the load carrying quality of plain bearings is associated with their operating conditions, load, relative surface-speed, clearance within the bearing, quality and quantity of lubricant, and operating temperature which affects lubricant viscosity.

A Plain Bearing

Figure 214 A picture showing a conventional plain bearing [WS36]

8.1.2 Rolling Bearing

Rolling bearings, also known as roller, anti-friction, or rolling element bearings, are the most common type of bearings used in industry. Functionality of rolling bearings is based on rolling motion in contrast to the sliding motion of plain bearings. The utilization of rolling elements between rotating and stationary surfaces hinders the friction to a fraction of that resulting with the use of plain bearings. Basically, rolling bearings use spheres or drums rolling between the rings to reduce friction; reduced friction allows tighter tolerances and thus higher precision than a plain bearing. Consequently, reduced bearing wear extends the time over which the machine functions accurately. Rolling bearings are generally employed for moderate to high speed applications [443]. Rolling bearings have the advantage of a good tradeoff between cost, size, weight, carrying capacity, durability, accuracy, and friction.

A Rolling Bearing

Figure 215 A picture showing a conventional ball-type rolling bearing [WS36]

The diameter size of rolling bearings ranges from 10 mm to a few meters and their load carrying capacity varies from a few tens of grams to many thousands of tones. The most typical kind of rolling bearing is ball bearing. Ball bearing has inner and outer races and a set of balls. Each race is a ring with a groove where the balls rest. The groove is usually shaped so the ball is a slightly loose fit in the groove. Therefore, in principle, the ball contacts each race at a single point. However, a load on an infinitely small point would cause infinitely high contact pressure. In practice, the ball flattens slightly where it contacts each race, much as a tire flattens where it touches the road. The race also dents slightly where each ball presses on it. Thus, the contact between ball and race is of finite size and has finite pressure. Most rolling element bearings use retainers or cages to keep the balls separate. This reduces wear and friction, since it avoids the balls rubbing against each other as they roll, and precludes them from jamming [242].

Components of a Typical Ball Bearing

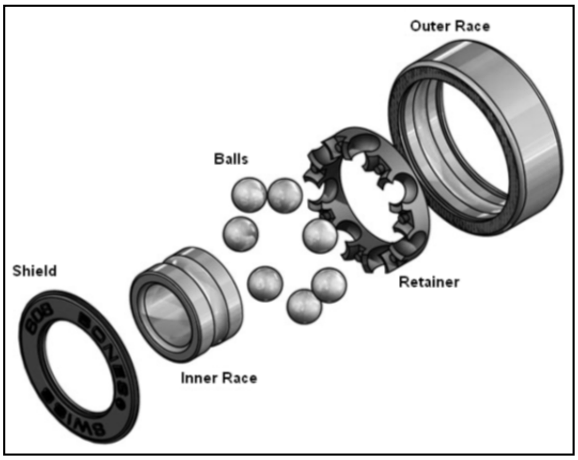


Figure 216 A picture presenting schematic of a ball rolling bearing assembly [WS20]

It is very seldom to have defectively manufactured bearings delivered to customers. As Mobley declares, defectively manufactured bearings only contribute to 2% of total in-plant bearing failures [443]. Bearing failure is usually associated with misalignment, imbalance, resonance and inappropriate lubrication. Most of these problems are usually result from dirt, shipping damage, improper storage and handling, installation damage, use of wrong bearing, overloading, improper lubricating practices, and loose foundation. Each of the mentioned conditions can eventually damage a bearing while two or more of these occurring simultaneously may give rise to a disaster.

Table 61, in the next page, provides a conducted problem and cause analysis for all types of bearings in general. As it can be easily construed from the below table there is a wide range of causes which result in a problem or problem-symptom associated with bearings; nevertheless, not all of these causes have equal probability of occurrence or importance weight. Hattangadi explains that the most common causes of both plain and rolling bearings in order of probability of occurrence are as followings [256]: (1) lack of lubricant, (2) lubricant deterioration, (3) contamination or dirt, (4) excessive loading, (5) inadequate clearance, (6) excessive clearance, (7) excess of lubricant, (8) thermal expansion, (9) wrong installation, and (10) bearing slippages.

Table 61 Problem and cause analysis of bearing

Object: Bearing Cause Problem	Corrosion	Seal wear	Cage wear	Oil foaming	Seal rubbing	Race turning	O-ring failure	Fretting wear	Shaft deflection	Electrical arcing	Rotor unbalance	Pinched bearing	Clogged breather	Housing distortion	Out-of-round shaft	Wrong installation	Lubricant churning	Race misalignment	Housing resonance	Flatted roller or ball	Excessive clearance	Excessive lubrication	Blocked oil passages	Contamination or dirt	Inadequate lubrication	Lubricant deterioration	Improper shaft attitude	Thermal race expansion	Thermal shaft expansion	Variable rolling elements	Bearing slipping on shaft	Bearing slipping in housing	Inadequate bearing clearance	Fatigued race or rolling element
Vibration	X		X			X				X	X				X	X		X	X		X			X						X			X	X
Noisiness					X							X			X					X				X	X	X				X	X	X		
Overheating	X		X	X	X	X								X		X						X	X		X								X	
Shaft binding					X									X							X			X		X			X				X	
Turning on shaft					X			X	X							X												X						
Lubricant seepage		X		X			X						X				X					X			X		X							

8.2 Compressors

Air/gas compressors have a wide range of capacity and pressure starting from very small machines of capacity of a few liters per minute and pressure of the order of a few kilograms per square centimeter, to very large units of capacity in thousands of liters per minute and pressure of order of several hundred kilograms per square centimeter. Typically, small compressors are employed for operating of small devices such as machinery brakes, doors and switches while the large ones are utilized in the main process in various chemical and processing industries. Taking into account the design and functionality, there are two main types of compressors: centrifugal and positive displacement. The later type is also divided into two major sorts: rotary and reciprocating.

8.2.1 Centrifugal Compressor

The centrifugal air/gas compressor is a dynamic compressor whose operating mechanism is associated with energy transfer from a rotating impeller to the air/gas. This type of compressors generates high pressure discharge by dynamic displacement which is converting angular momentum imparted by the rotating impeller. For dynamic displacement to be effectively taken place, centrifugal compressors rotate at higher speeds than the other compressors types. These compressors are appropriate for higher capacity as the air/gas flow through their body is continuous. The most common method to control capacity of a centrifugal compressor is to adjust the inlet guide vanes, by closing of which, volumetric flows and capacity are decreased [388].

A Centrifugal Compressor

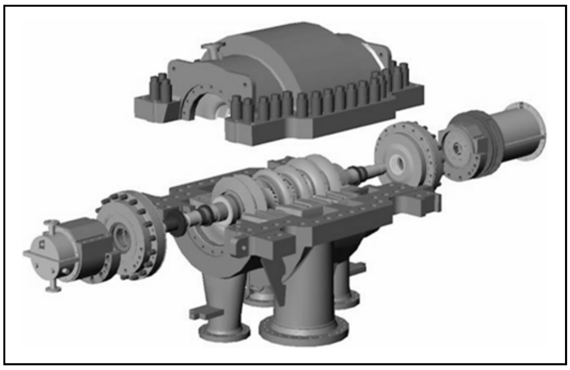


Figure 217 A picture indicating schematic of an industrial centrifugal compressor [WS49]

The most common failure mode of centrifugal air/gas compressors is aerodynamic instability which is usually generated by variable demand and restraints on air/gas inflow. Trapped liquids or solids can also become predicaments by reducing the remaining lifetime of compressors. Therefore, in handling dirty air/gas, special filters or open-type impellers must be used.

In fact, such an open structure provides the chance to handle a moderate amount of dirt or small solids in the inlet fluid supply; nevertheless, use of inlet filters is strongly recommended for all operating conditions [575]. Table 62 provides a compact problem and cause analysis for centrifugal compressors.

Table 62 Problem and cause analysis of centrifugal compressor

Object: Centrifugal Compressor Cause Problem	Oil leakage	Misalignment	Worn bearings	Liquid slugging	Damaged rotor	Shaft deflection	Inadequate flow	Rotor imbalance	Dry gear coupling	Damaged coupling	Improper oil condition	Inadequate oil reservoir	Loose rotor components	Wrong bearing clearance	Operating in surge region	Plugged oil pump suction	Rough rotor shaft surface	Very low operational speed	Very high inlet temperature	Blocked oil filter or strainer	Very high operational speed	Loose or warped foundation	Deposits on diffuser or rotor	Leakage in discharge piping	Change in system resistance	Broken or loose bolted joints	Missing bearing lube oil orifice	Pipes pull on other components	Leakage in lube oil cooler tubes	Leakage in oil pump suction piping	Improperly assembled components	Wrong pressure control valve setting	Stuck open or wrongly set relief valve	Failure of main and auxiliary oil pumps	Defective temperature gauge or switch
Vibration		X	X	X	X			X	X	X			X	X	X						X		X			X		X			X				
Noisiness		X		X	X					X			X	X	X								X					X			X				
Stumbled motor			X														X							X				X			X				X
Surging compressor							X																X		X										
Constant unloading				X		X		X									X					X						X			X				
Low lube oil pressure	X											X				X		X		X							X			X		X	X	X	X
Contaminated lube oil																												X	X						
Discharge pressure deficit																		X	X					X											
Frequently misaligning units		X																										X							
Overheated bearing oil drain			X								X						X																		X

8.2.2 Rotary Compressor

One of the major types of positive displacement compressors is rotary compressors. The most common rotary air/gas compressor is the single stage helical or spiral screw compressor. These compressors consist of two rotors within a casing where the rotors compress the air or gas internally. Rotary screw compressors do not have valves and they are basically oil cooled having the oil sealed the internal clearances. As the cooling process is carried out inside the compressor, the operating parts do not usually experience extreme temperatures. Hence, rotary compressors are considered to be units with higher reliability and continuous duty. Besides, they are easy to maintain and operate [251].

Capacity control for these compressors is accomplished by either variable speed or variable compressor displacement. In the latter control method, a slide vane is positioned in the casing. As the compressor capacity is reduced, the slide vane opens, bypassing a portion of the compressed air/gas back to the suction. Advantages of the rotary screw compressor include smooth, pulse-free air output in a compact size with high output volume over a long life. There are also oil-free, air/water cooled rotary compressors which utilize special configurations to compress air/gas without having oil in the compression chamber yielding true oil free air/gas [251].

A Rotary Compressor

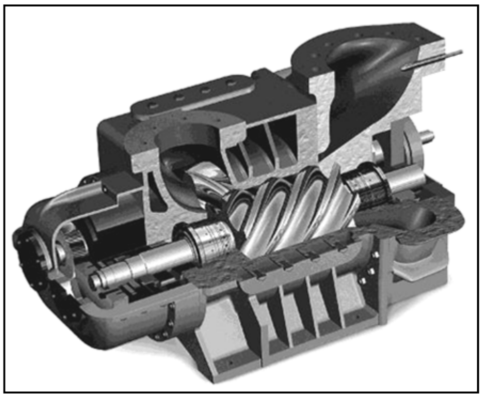


Figure 218 A picture presenting a side-cut of an industrial screw-type rotary compressor [WS49]

The most common reason for rotary compressor failure or component damage is process instability. Rotary compressors are designed to provide a constant volume and pressure of air/gas. Hence, they are exceptionally susceptible to any change in the conditions of their inlet or discharge sections. A very small variation in pressure, temperature or volume of air/gas can instantaneously bring about a failure [440]. Table 63 presents an overview of problem and cause analysis of rotary compressors.

Table 63 Problem and cause analysis of rotary compressor

Object: Rotary Compressor Cause Problem	Misalignment	Very low speed	Dirt or chips in fluid	Motor or driver failure	Inadequate fluid supply	Very high inlet pressure	Binding rotating element	Internal component wear	Wrong rotational direction	Very high inlet temperature	Very high discharge pressure	Blocked suction filter or strainer	Air leakage into piping or shaft seal	Pipe pulling on compressor's casing	Stuck open or wrongly set relief valve
Vibration	X				X	X	X				X	X	X	X	
Noisiness	X				X		X				X	X	X	X	
Excessive wear	X		X		X		X				X			X	
Excessive heat	X						X				X			X	
Stumbled motor		X			X		X				X				
No fluid delivery				X				X	X			X			
Insufficient capacity		X			X	X		X		X	X	X	X		X
Raised fluid temperature											X				
Raised motor temperature	X						X		X			X		X	
Inadequate discharge pressure		X			X			X	X			X	X		X
Disproportionate power demand	X						X				X			X	

8.2.3 Reciprocating Compressor

Reciprocating compressors are the second major types of positive displacement compressors which raise the pressure of the air/gas inflow by decreasing its volume. In other words, they take in successive volumes of air/gas which is confined within a closed space and escalating this fluid to a higher pressure. They achieve this by piston and cylinders as the compressing and displacing elements. Reciprocating compressor is referred as single acting when the compressing is accomplished using only one side of the piston. A compressor which utilizes both sides of its piston is denoted as double acting. Load reduction is achieved by unloading individual cylinders. Typically, this is done by throttling the suction pressure to the cylinder or bypassing air either within or outside the compressor. Capacity control is realized by varying speed in engine-driven units through fuel flow control. These compressors are available either as air-cooled or water-cooled in lubricated and non-lubricated configurations and provide a wide range of pressure and capacity selections [84].

A Reciprocating Compressor

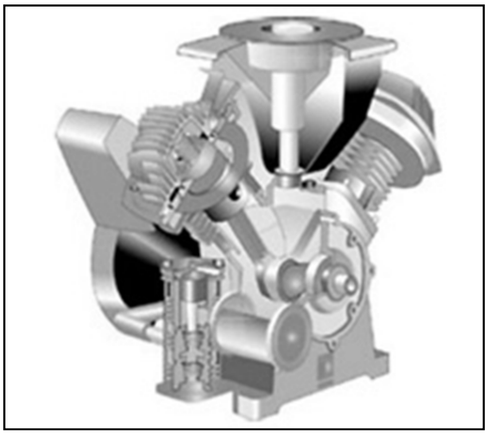


Figure 219 A picture indicating schematic of an industrial reciprocating compressor [WS49]

Similar to all reciprocating machines, reciprocating compressors normally create higher vibration levels due to the impact as each piston reaches top and bottom halt centers of its stroke. Valve failure is the most common failure mode for reciprocating positive displacement compressors because of their high cyclic rate. In addition, poor maintenance of lubrication system components such as filters and strainers can result in premature failures [440]. Table 64 shows an undertaken problem and cause analysis for reciprocating compressors.

Table 64 Problem and cause analysis of reciprocating compressor

Object: Reciprocating Compressor Cause Problem	Slipped belts	Worn cylinder	Misalignment	Worn bearings	Very tight belts	Defective gauge	Blocked oil filter	Blocked air filter	Very low oil level	Inappropriate oil	Wrong assembly	Very high oil level	Loose foundation	Excessive oil feed	Defective air filter	Loose motor rotor	Electrical problems	Improper intake pipe	Defective safety valve	Inadequate ventilation	Inadequate lubrication	Leakages from gaskets	Defective oil relief valve	Loose pulley or flywheel	Dirt or chips into cylinder	Very low incoming voltage	Wrong rotational direction	Improper rotational speed	Undersize electrical motor	Excessive leakage in system	Worn or defective rod packing	Above rating discharge pressure	Very high air discharge temperature	Worn, dirty or defective cylinder valves
Vibration		X	X								X		X			X								X				X				X		
Noisiness	X	X	X	X				X		X	X	X	X	X		X		X	X		X	X		X						X	X	X		X
Worn valve										X	X			X	X						X				X									
Start failure					X												X									X	X		X		X			
Overheated motor		X		X	X			X		X							X	X	X	X	X	X				X		X	X	X		X		X
Excessive oil pumping								X		X		X						X			X													
Overheated components		X	X	X	X			X	X	X		X						X		X	X	X						X			X	X		X
Very long operating cycles		X						X										X			X	X								X		X		X
Low crankcase oil pressure				X		X	X		X	X													X											
Worn piston rod or packing		X								X	X			X	X						X	X			X						X	X		X
Excessive receiver pressure						X																										X		
Excessive intercooler pressure		X				X																X										X		X
Inadequate discharge pressure	X	X				X		X										X	X			X								X	X			X
Output less than rated capacity	X	X						X										X	X			X								X	X	X		X
Inadequate intercooler pressure		X				X		X										X	X			X								X				X
Worn piston, piston ring or cylinder		X								X	X				X						X	X			X							X		X
Excessive outlet water temperature																						X						X				X	X	X
Formation of carbonaceous deposits		X								X		X		X	X					X		X			X		X	X			X	X	X	X
Very high discharged air temperature		X						X				X						X	X	X	X	X					X	X		X	X	X		X

8.3 Control Valves

Control valves are valves employed to control conditions such as flow (i.e. flow velocity), pressure, temperature, and fluid level by fully or partially opening or closing in response to a manual actuator or signals received from controllers that compare a set-point to a process variable whose value is provided by sensors that monitor changes in such conditions. The automatic actuating (i.e. opening or closing) of control valves is done by means of pneumatic, hydraulic, or electrical systems [50].

8.3.1 Manually Actuated Control Valve

Manually actuated control valves are limitedly used in pneumatic or hydraulic circuits. In general, this type of valves are used as isolation valves that are activated when the circuit or fluid system has to be shut down for maintenance and repair, or when direct operator input is needed to operate one of the system components. Indeed, manual control instruments such as levers, cams and palm buttons can be utilized as the primary actuator on most control valves; however, these actuators are usually used in combination with a secondary actuator such as a spring return or detent to guarantee faultless operation of the control valve and its circuit. Spring returns are commonly used for applications in which the valve is required to stay open or close only when the operator holds the manual actuator. Valves with detent are designed to remain in the last position selected by the operator until manually turned to another position [574].

A Manual Control Valve

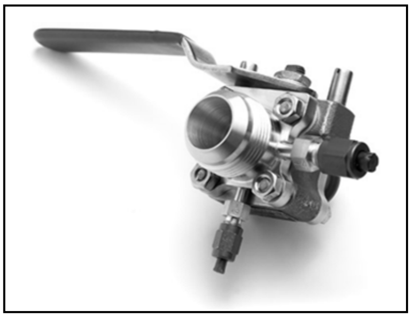


Figure 220 A picture representing a manually actuated control valve [WS111]

In practice there are limited number of frequent control valve failure modes; the most common problems of manual control valves are usually associated with either leakage or valve's operation failure. Nevertheless, if a root cause analysis is required to be undertaken, special attention should be given to the valve's actuator. In fact, many of the valves problems are basically related to the actuator but not the structure of the valve itself. Table 65 represents a problem and cause analysis carried out for manually actuated control valves.

Table 65 Problem and cause analysis of MA control valve

Object: Manually Actuated Control Valve Cause Problem	Galling	Corrosion	Tightly packed	Loosely packed	Excessive wear	Undersized valve	Jumped valve stem	Damaged seal or seat	Excessive line pressure	Damaged threads or lever	Contamination or dirt in valve seat
Valve failure to open	X		X				X	X	X	X	
Valve failure to close	X		X		X		X	X	X	X	X
Leakage around stem				X					X		
Leakage through valve		X			X				X		X
Excessive pressure drop						X			X		X
Very slow valve opening or closing						X					

8.3.2 Automatically Actuated Control Valve

Automatically actuated control valves are available in a variety of sizes, configurations and materials of construction. The process control valves are actuated by pneumatic, hydraulic or electrical systems. Pneumatic actuators are usually used for simple start/shut applications. In this case, valve can be repositioned as long as there is enough air volume and pressure for activation. If there is not enough air supply for activation or the process system pressure is too high, the ability of the actuator can be considerably diminished. Such valves are not suitable for precision flow control as the compressibility of air does not effectively provide smooth and accurate valve repositioning. Hydraulic actuators, conversely, can provide a precise means of controlling valves in a wide range of applications. Electronic actuators consist of high torque electric motors which can offer reliable control valve actuation [574].

Similarly, the automatic fluid-power control valves are divided into two large groups depending on if they have pilot or solenoid actuating system. Pilot actuators denote all the actuators in which a secondary source of fluid or gas pressure is applied to one side of a sealing device such as a piston or diaphragm. Having this secondary pressure stayed within preset limits, the sealing device stops the valve's control mechanism. If the secondary pressure is outside of the preselected limit range, the actuator shifts and forces the valve's primary control mechanism to reposition. Solenoid actuators include a coil that generates and electrical field when energized. The magnetic forces created by this field compel a plunger that is attached the valve's primary control mechanism. Solenoid actuators are usually used in conjunction with a secondary actuator [443].

An Automatic Control Valve

Figure 221 A picture representing a pneumatically actuated control valve [WS103]

Similar to their peers, many of the problems of automatically actuated control valves in both process and fluid-power systems are indeed actuator problems. Quite commonly, the actuator failures are the reason an automatic valve fails to correctly open, close or seal. For instance, if the actuator is jammed on or off, it may cause failure of the valve mechanism. This over-torque of the valve's sealing device may bring about partial damage or complete failure of the seal or it may even freeze the valve stem, either of which cause total valve failure. Table 66 supplies a problem and cause analysis of automatically actuated control valves.

Table 66 Problem and cause analysis of AA control valve

Object: Automatically Actuated Control Valve Cause Problem	Galling	Corrosion	Solenoid failure	Wrong valve type	Damaged seal or seat	Excessive line pressure	Very low guide pressure	Very high guide pressure	Defective solenoid wiring	Blocked guide pressure port	Contamination or dirt in valve seat
Valve failure to open	X	X	X	X	X	X	X		X	X	X
Valve failure to close	X	X	X	X	X	X		X	X	X	X
Leakage around stem		X			X	X	X			X	X
Leakage through valve						X					
Excessive pressure drop											X
Very fast valve opening or closing								X			
Very slow valve opening or closing						X					

8.4 Conveyors

Modern production systems require the use of material handling systems. Conveyors are common pieces of mechanical handling equipment that moves materials from one location to another. They include all fixed and portable equipment capable of moving material in a continuous or discontinuous manner between two or more points along a fixed path. While the material can be delivered intermittently, their drives function continuously. The direction of material movement can be horizontal, vertical, inclined or a combination of these three. Conveyors are especially useful in applications involving the transportation of heavy or bulky materials. Conveyor systems allow quick and efficient transportation for a wide variety of materials, which make them fully utilized in the material handling and packaging systems. Conventionally, industrial conveying systems are divided into either mechanical (e.g. chain and roller types) or pneumatic conveyors [189].

8.4.1 Chain Type Conveyor

Chain conveyors exploit a powered continuous chain system, carrying a series of single bars, palettes or pendants. The chain system is driven by a motor and a gearbox which provide the power to transfer the material. Many industry sectors use chain conveyor technology in their production lines. The automotive and automotive supply industries commonly use chain conveyor systems to convey car parts through the work stations. Chain conveyors also have widespread use in metal finishing and distribution industries [418].

A Chain Type Conveyor

Figure 222 A picture showing a chain type conveyor [WS29]

Typically, chain conveyors use a centered single or double chain configuration to realize transfer of material within their ductwork. The internal part of the ductwork should be free of defects or protrusions that may interfere with the movement of the conveyor's chain. The ductwork must be sized to supply adequate chain clearance. A long horizontal run followed by an upturn is not desirable due to generated radial thrust. All bends must have a large enough radius to provide smooth transition and even material movement. Besides, all drive system configurations should incorporate a single point of failure device like a shear pin to protect the conveyor against catastrophic failures resulted from blockages or obstructions that may lock the chain. Most of chain type conveyors' failures are associated with faults in their chain(s), ductwork, motor or gearbox [443]. Table 67 shows a problem and cause analysis performed for chain type conveyors.

Table 67 Problem and cause analysis of chain type conveyor

Object: Chain Type Conveyor Cause Problem	Blocked chain	Misaligned chain	Misaligned gears	Too loose drive chains	Inadequate lubrication	Wrongly mounted gears	Very high product weight	Excessive product volume	Conveyor ductwork blockage	Over-filled conveyor when idle	Excessive moisture in product	Defective motor speed control unit	Conveyor chain pulling on ductwork	Unempty conveyor before shut down
Vibration			X		X	X								
Noisiness		X	X		X	X							X	
Worn bearing	X	X	X		X									
Stumbled motor	X						X	X	X	X	X			X
Worn drive gears					X	X								
Broken shear pin		X	X				X			X				X
Overheated motor	X	X	X		X		X	X	X					
Repeated conveyor blockage		X								X	X			X
Output less than rated capacity	X			X			X	X	X		X	X		

8.4.2 Roller Type Conveyor

Powered roller type conveyors are usually driven via a shaft or chain beneath the rollers. These conveyors are suitable for light weight applications up to a few tens of kilograms for long distance. In shaft-driven roller conveyors which are also known as line shaft conveyors, a single shaft runs below the rollers along the length of the conveyor. On the shaft there are a series of spools. A rubber O-ring runs from a spool on the powered shaft to each roller. As the shaft is powered, the rubber O-ring acts like a chain between the spool and the roller making the roller rotate. The rotating of the rollers moves the material along the conveyor. The shaft is usually driven by an electrical motor, which is generally controlled by an electronic programmable logic controller (PLC). Roller type conveyors carry out quiet operation and undergo easy installation and maintenance. A demerit of the roller type conveyors is that they can only be employed to move particular materials of certain size and shape not falling between the rotating rollers [430].

A Roller Type Conveyor

Figure 223 A picture presenting a roller type conveyor [WS17]

Most of the problems associated with roller type conveyors can be attributed to either improper installation or abnormal induced loads. Installation problems are commonly caused by misalignment where the rolls are not perpendicular to the shaft, travel path of the chain or belt, or direction of transported material. When the rolls are vertically or horizontally misaligned, the load induced by the transported material cannot be evenly spread across the roll face or to the support bearings. Consequently, both the roll face and bearings undergo abnormal wear and may fail earlier than expected. In addition, operating variables such as chain, belt or strip tension or tracking can be sources of chronic reliability problems. These factors can also result in a non-uniform load distribution across the roll face and bearings which accelerate wear and occurrence of related failures [440]. Table 68 indicates an undertaken problem and cause analysis for roller type conveyors.

Table 68 Problem and cause analysis of roll type conveyor

Object: Roll Type Conveyor Cause Problem	Misalignment	Excessive load	Poor roll grinding	Damaged roll face	Defective roll bearing	Too loose product tension	Too much product tension	Move w. roll's natural frequency	Product tension or tracking problem	Move w. structure's natural frequency
Vibration	X							X		X
Noisiness	X									X
Bearing failure	X			X			X	X		
Overheated motor	X	X					X			
Damaged roll neck	X			X			X			
Poor product quality	X		X	X	X	X	X	X	X	X
Abnormally worn roll face	X						X		X	X
Anomalous product tracking	X			X			X	X	X	X
Disproportionate power demand	X	X			X		X			

8.4.3 Pneumatic Conveyor

Pneumatic conveyors are basically quite simple and are eminently suitable to transport dry, free-flowing, powdered and granular materials in sites and factories. Pneumatic conveying systems include pipes or ducts known as transportation lines that carry mixture of materials and a stream of air. These materials range from dry pulverized to light powdery substances like cement, and can be transported conveniently to various destinations by means of a stream of high velocity air through transportation lines. Indeed, a pneumatic conveying system requires a source of compressed air/gas, a feed device, transportation lines, and a receiver to disengage the conveyed material and carrier air/gas. Such a system is totally enclosed, and if it is required, the system can function entirely without moving parts coming into contact with the conveyed substances or materials. High, low or even negative pressures can be used to transport the materials [434].

A Pneumatic Conveyor

Figure 224 A picture showing a pneumatic conveyor [WS39]

Pneumatic conveyors are either carrier or dilute-phase conveying systems; carrier systems simply push items from one entry point to one exit point. Dilute-phase systems use push/pull pressure to guide materials through various entry and/or exit points. Three basic methods that are used to generate high velocity air/gas stream are: (i) suction or vacuum methods which exploit pressures practically 0.4 to 0.5 atm below atmospheric pressure, (ii) pressure type methods in which positive pressures (i.e. 6 atm and onwards) are used to push material from one point to the next, (iii) combination methods in which a suction system is used to convey material from a number of loading points and a pressure system is employed to deliver it to a number of unloading points [332].

Like previously noted conveying systems, some of the problems of pneumatic conveyors are linked to misalignments and improper installation including wrong piping configuration. Nevertheless, flow restrictions, contamination, inadequate lubrication can be also considered as major causes of premature failures in these systems. In fact, an inherent weakness of pneumatic conveying systems is their potential for blockage. For instance, as a system is shut down or the velocity is reduced below the minimum limit to keep the conveying material suspended, the material drops out or settles in the piping or ductwork resulting in flow restrictions. Or, when the exit point of the conveying system such as a storage, machine or vessel cannot accept the entire delivered flow of material, the conveying material starts to back up and compress which eventually forms a solid plug blocking the piping [574]. Table 69, in the next page, provides a problem and cause analysis undertaken for pneumatic conveyors.

Table 69 Problem and cause analysis of pneumatic conveyor

Object: Pneumatic Conveyor Cause Problem	Misalignment	Improper fan size	Binded or tied rotor	Blockage by product	Mechanical imbalance	Inadequate lubrication	Leakage through pipes	Aerodynamic imbalance	Very low product density	Very high start-up torque	Very high product density	Contamination in product	Wrong piping configuration	Pipe blockage by foreign object	Excessive moisture in product or pipe	Product compaction during stoppages
Vibration	X		X		X	X		X								
Noisiness	X		X		X											
Bearing failure	X		X		X	X		X								
Stumbled motor		X	X	X				X		X	X		X	X	X	X
Fan or blower failure	X	X	X	X	X	X		X			X				X	
Contamination in product							X					X			X	
Repeated conveyor blockage													X	X	X	X
Output less than rated capacity		X		X			X				X		X	X	X	X
Output more than rated capacity									X							

8.5 Fans

Fans produce air flows with high volume and low pressure, as opposed to compressors which produce high pressures at a comparatively low volume. Centrifugal and axial fans are used in many industries for main processes and also as auxiliary machines for enhancing the output of other equipment such as electrical motors and transformers. Some fans are mounted directly on or inside these machines and some may be mounted and driven separately. In some cases fluids are employed for cooling of the equipment and fans are utilized for cooling of that fluid. On the whole, failures of fans are relatively less frequent in comparison with other industrial machinery and equipment as they are simply made up of cast or welded impellers inside steel casings. Despite this simplicity, fan failures do occur due to design and manufacturing deficiencies, and because of poor installation and operating conditions [256].

8.5.1 Centrifugal Fan

Centrifugal fan, also known as squirrel-cage fan, is a mechanical device for moving air or gases. It has a fan wheel composed of a number of fan blades, ribs, or vanes, mounted around a hub. The hub turns on a drive shaft that passes through the fan housing. The air/gas enters from the side of the fan wheel, turns 90 degrees and accelerates due to centrifugal force as it flows over the fan blades and exits the fan housing. Centrifugal fans can generate pressure rise in the air/gas stream. Accordingly, they are well-suited for industrial processes and air pollution control systems. They are also common in central heating and cooling systems [81].

There are three major types of centrifugal fans, which are namely radial, forward-curved and backward-curved fans. Radial or paddle-blade fans are industrial workhorses because of their high static pressures and ability to handle heavily contaminated airstreams. Due to their simple design, radial fans are well suited for high temperatures and medium blade tip speeds. Industrial exhaust fans fan into this category. Forward-curved or multi-vane fans are used in clean environments and operate at lower temperatures. They are well suited for low tip speed and high airflow work and moving large volumes of air against relatively low pressures. Backward-curved or backward-inclined fans are more efficient than forward curved fans. They are able to reach their peak power consumption and then power demand drops off well within their useable airflow range. These types of fans are known as non-overloading as changes in static pressure do not overload the motor [81].

A Centrifugal Fan

Figure 225 A picture showing an industrial forward-curved centrifugal fan [WS31]

Centrifugal fans are very susceptible to variations in suction and discharge conditions. In addition to variations in ambient conditions like temperature and humidity, control variables can have a considerable effect on fan's performance and reliability. The majority of the centrifugal fan problems are directly or indirectly linked to wrong installation, improper application, and inappropriate operation and maintenance. The most frequent problem causes of centrifugal fans are known to be aerodynamic instability, dirt and contamination adhering fan's rotating elements, inappropriate rotational speeds, and loose foundation [443]. Table 70 represents a problem and cause analysis carried out for centrifugal fans.

Table 70 Problem and cause analysis of centrifugal fan

Object: Centrifugal Fan Cause Problem	Imbalance	Worn coupling	Worn bearings	Dirt in bearings	Shaft deflection	Damaged motor	Damaged wheel	Loose foundation	Irregular end thrust	Improper lubrication	Defective stuffing box	Broken or loose joints	Excessive belt tension	Air leakages in system	Aerodynamic instability	Improperly wired motor	Inadequate belt tension	Externally radiated heat	Very low rotational speed	Wrong rotational direction	Very high rotational speed	Wheel pulling on fan's casing	Loose dampers or inlet vanes	Excessive lubrication in bearings	Poor fan inlet or outlet conditions	Wrongly adjusted dampers or inlet	Wheel mounted backward on shaft	Abnormal specific gravity or density	Induced vibration from other sources	Fan delivery more than rated capacity	Misaligned bearings, coupling or belt
Vibration	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X			X	X	X	X					X	X	X	X
Noisiness	X		X					X		X					X	X	X		X			X							X		X
Stumbled motor										X	X		X			X			X		X	X									
Uneven operation								X						X	X																
Overload on driver					X					X	X					X				X		X						X		X	X
Insufficient capacity							X							X	X				X	X					X	X	X				
Overheated bearings	X			X	X		X	X	X			X	X		X			X			X	X		X					X		X
Intermittent operation																			X		X										
Reduced bearing useful life					X										X						X										
Inadequate discharge pressure							X							X					X	X					X	X	X				
Disproportionate power demand					X						X																	X			X

8.5.2 Axial Fan

The axial fans have blades that force air to move parallel to the shaft about which its blades rotate. The way these fans work can be compared to a propeller on an airplane: the fan blades generate an aerodynamic lift that pressurizes the air. This type of fans, being inexpensive, compact and light, is used in various applications, ranging from small cooling fans in electronic equipment to the giant fans used in wind tunnels. There are three major types of axial fans, which are namely tube-axial, vane-axial and propeller fans. Tube-axial fans have a wheel inside a cylindrical housing, with close clearance between blade and housing to improve airflow efficiency. The wheel rotates faster than propeller fans, enabling operation under high pressures. Vane-axial fans are similar to the former type, but with addition of guide vanes that improve efficiency by directing and straightening the flow. As a result, they have a higher static pressure with less dependence on the duct static pressure [81].

Vane-axial fans are the most energy efficient fans available. Propeller fans usually operate at low speeds and moderate temperatures. They experience a large change in airflow with small changes in static pressure. They handle large volumes of air at low pressure or free delivery. Propeller fans are often used indoors as exhaust fans. Outdoor applications include air-cooled condensers and cooling towers. However, their efficiency is lower than the former two types and around 50% [81].

An Axial Fan

Figure 226 A picture showing an industrial tube-axial fan [WS56]

Axial fans are not suitable for corrosive or explosive environments as their motors and bearings cannot be protected. Applications in which concentrations of airborne abrasive are present should also be shunned. Generally, axial fan problems taken place due to process instability initiated by start/stop operation, demand variations, and mechanical failures resulted by misalignments and worn internal parts [574]. Table 71 provides a problem and cause analysis undertaken for axial fans.

Table 71 Problem and cause analysis of axial fan

Object: Axial Fan Cause Problem	Very low speed	Motor or driver failure	Coupling misalignment	Excessive inlet moisture	Binding rotating element	Worn internal component	Wrong rotational direction	Pipe pulling on fan's casing	Excessive inlet temperature	Excessive discharge pressure	Blocked suction filter or strainer	Dirt or chips in air/gas supply inlet	Inadequate air/gas supply suction	Air leakage into piping or shaft seal	Stuck open or wrongly set relief valve
Vibration			X		X	X		X		X	X		X	X	
Noisiness			X		X	X		X		X	X	X	X	X	
Excessive wear			X		X			X		X		X	X		
Excessive heat			X		X			X							
Stumbled motor	X				X					X			X		
Insufficient capacity	X			X		X			X	X			X	X	X
No air/gas conveyance		X				X	X				X				
Elevated motor temperature			X		X		X	X			X				
Elevated air/gas temperature										X					
Inadequate discharge pressure	X					X	X				X				X
Disproportionate power demand			X		X			X		X			X	X	

8.6 Gear Systems

A gear is a disk shaped machine element with teeth on its periphery within a transmission system that transmits rotational force to another gear or device. Depending on their construction and arrangement, geared devices can transmit forces at different speeds, torques or in a different direction from the power source. The most common situation is for a gear to mesh with another gear, but a gear can mesh with any device having compatible teeth, such as a linear moving rack [169]. Gears of unequal diameters can be combined to produce a mechanical advantage, so that the rotational speed and torque of the second gear are different than those of the first.

There are a wide range of gears used for various applications in different industries. The four most frequently used industrial gear types are namely spur, helical, worm, and bevel gears [396]:

- **Spur gear**: It is the simplest and most common type of gear. Spur gear is in the form of a disk with radially projected teeth. The leading edges of spur gear teeth are aligned parallel to the axis of rotation. This kind of gears can only mesh correctly if they are fitted to parallel axles. These gears are used in applications where considerable noise emission does not matter. But in cases where level of noise emission does matter and high operational speeds are also required, nylon or nonmetallic spur gears are recommended.

- **Helical gear**: The leading edges of the helical gear teeth are not parallel to the axis of rotation, but are set at an angle. Since the gear is curved, this angling causes the tooth shape to be a segment of a helix. The angled teeth engage more gradually than do spur gear teeth. This causes helical gears to run smoother and quieter than spur gears. Helical gears also offer the possibility of using nonparallel shafts. However, a helical gear undergoes a resultant thrust along its axis which needs to be accommodated by appropriate thrust bearings, and a greater degree of sliding friction between the meshing teeth that is often addressed with specific additives in the lubricant.

- **Worm gear**: This type of gears is usually used when, in a single step, a large speed reduction ratio is required between crossed axis shafts which do not intersect. A basic helical gear can be used, but the power which can be transmitted is low. A worm drive consists of a large-diameter worm wheel with a worm screw meshing with teeth on the periphery of the worm wheel. As the worm is rotated, the worm wheel rotates due to the screw-like action of the worm. Proper lubrication of these gears is critical as there is continuous sideway sliding motion. This makes maintaining a hydrodynamic oil wedge very hard. The result is that worm gears operate under conditions of boundary lubrication.

- **Bevel gear**: This gear is cut from conical blanks and it is usually employed to connect intersecting shaft axes. The connecting shafts are generally perpendicular; and sometimes, one shaft drives a bevel gear which is mounted on a through shaft, resulting in two output shafts. The point of intersection of the shafts is called the apex, and the teeth of the two gears converge at the apex. The design of bevel gears results in thrust forces away from the apex. With the bearing limitations, the bevel gears have to be carefully selected to ensure that they are not thrown out of alignment as they are loaded. These gears are used widely in machine drive systems to support 90° direction changes.

Different Types of Gears

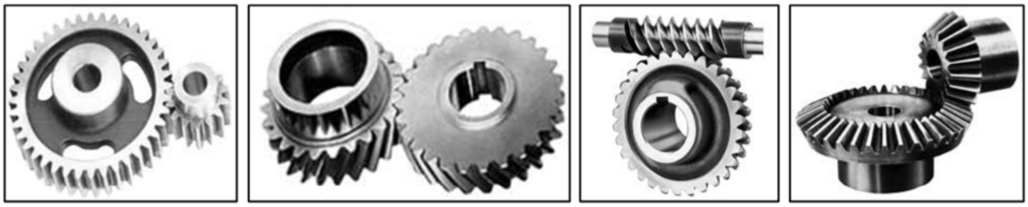


Figure 227 A picture showing spur, helical, worm and bevel gear types from left to right [WS42]

In practice, two or more gears usually form a gear system known as a gearbox or a gear set to perform certain functions. One of the major causes of gear failure in such systems is bidirectional operation of these gear sets although they are usually designed for operation in one direction only [440].

A Gear Set

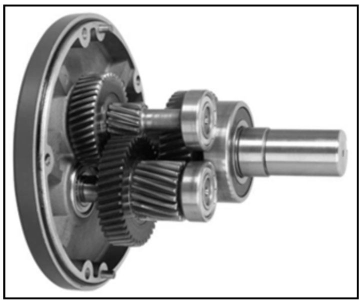


Figure 228 A picture of a gear set with helical gears [WS55]

In general, gears fail either instantaneous due to a sudden external load or over time because of bending or surface fatigue, long term overload, abrasive or erosive wear, or corrosion. Each of these factors may itself denote other root causes of the failure. For example, bending fatigue cracking shows that the cantilever strength of the teeth has been exceeded over some time. Or, surface fatigue indications such as spalling and pitting are formed when the surface loads are excessive or the lubricant film is inadequate [534]. Gear failures due to contamination or dirt entering the system, improper or lack of lubrication, and loose foundation or joints are also quite frequent [256]. Table 72 indicates a problem and cause analysis for gear systems.

Table 72 Problem and cause analysis of gear system

Object: Gear System Cause Problem	Overload	Corrosion	Worn bearing	Misalignment	Worn coupling	Elliptical gears	Shaft deflection	Damaged motor	Loose foundation	Excessive backlash	Improper lubrication	Contamination or dirt	Broken or loose joints	Wrongly mounted gears	Wrongly mounted shafts	Wrong rotational direction	Excessive torsional loading	Unsuitable gearbox application	Surpassing motor brake power rating
Vibration		X	X	X	X	X	X	X	X		X		X	X	X	X		X	
Noisiness			X	X					X		X			X	X				
Stumbled motor								X			X						X		
Overload on driver	X					X	X	X								X	X	X	X
Worn or broken gear	X	X		X						X	X	X					X	X	
Overheated bearings	X			X			X		X		X		X				X	X	
Uneven torsional power				X		X			X	X	X						X		
Inadequate power output	X					X								X		X	X		X
Reduced bearings useful life	X			X			X				X						X		

8.7 Pumps

A pump is a machine which is used to move fluids, such as liquids, slurries, and gases. A pump displaces a volume by physical or mechanical action. Pumps are the driving force behind the fluid transfer in systems, plants and processes. Unless the system in question is redundant, a failed pump inevitably will cause a loss of production. The more expensive a pump is, and the more complex the process cycle within which it serves, the more important it is to keep steady tabs on the condition of the pump. This applies in particular to pumps that are known to be somewhat impaired but have not yet failed. Pumps come in a variety of sizes for a wide range of applications. They can be classified according to their basic operating principle as centrifugal, and rotary or reciprocating displacement pumps [456], [641]. Keeping pumps operating productively for long periods of time requires careful pump design selection, proper installation, careful operation, the ability to observe changes in performance over time, and in the event of a failure, the capacity to thoroughly investigate the cause of the failure and take measures to prevent the problem from re-occurring. Pumps that have been: properly sized, are dynamically balanced, that sit on stable foundations with good shaft alignment, with proper lubrication, infrequently experience catastrophic failure [483].

8.7.1 Centrifugal Pump

Centrifugal pumps consist of an impeller and an intake at their center. These are arranged so that when the impeller rotates, liquid is discharged by centrifugal force into a casing which surrounds the impeller. The casing reduces the velocity of the fluid which leaves the impeller at a high velocity. This velocity is converted to pressure which is needed to discharge the fluid. Some of characteristics of centrifugal pumps can be named as smooth flow through the pump and uniform pressure in the discharge pipe, low cost, and an operating speed that allows for direct connection to steam turbines and electric motors. Centrifugal pumps are also more suitable for handling large capacities of liquids than positive displacement pumps [456].

A Centrifugal Pump

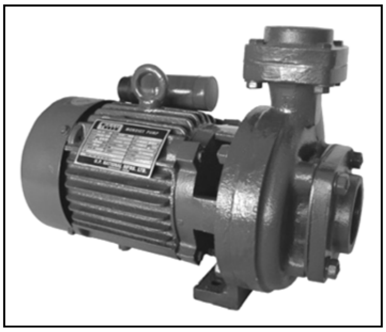


Figure 229 A picture representing a centrifugal pump [WS98]

Centrifugal pumps Centrifugal pumps are characterized by the relationship between the flow rate they produce and the pressure at which the flow is delivered. Pump efficiency varies with flow and pressure, and it is highest at one particular flow rate [641]. They are known to be very sensitive to variations in fluid condition such as viscosity, specific gravity and temperature, suction variations such as pressure and availability of continuous fluid flow, and variations in demand [54]. Mechanical failure of this type of pumps can take place for various reasons. Some are associated with cavitation, hydraulic instability and other system-related issues; others are linked with improper operation and maintenance such as misalignment, imbalance and seal leakage. Among all, cavitation is the most common cause of centrifugal pumps failure [575]. Table 73 provides a problem and cause analysis of centrifugal pumps.

Table 73 Problem and cause analysis of centrifugal pump

Object: Centrifugal Pump Cause Problem	Cavitation	Misalignment	Worn bearings	Shaft deflection	Rotor imbalance	Casing distortion	Driver imbalance	Clogged propeller	Leakage in system	Trapped air in fluid	Hydraulic instability	Clogged inlet strainer	Very high fluid viscosity	Very high specific gravity	Internal component wear	Driver electrical problems	Wrong rotational direction	Wrong impeller installation	Very low operational speed	Inadequate suction volume	Non-condensables in liquid	Unsuitable pumps in series	Very high operational speed	Unsuitable pumps in parallel	Inadequate suction pressure	Inappropriate mechanical seal	Inadequate flow through pump	Blockade in lines or pump housing	Total system head lower than design	Total system head higher than design
Vibration	X	X	X	X	X		X	X		X	X	X			X	X				X	X	X		X	X			X	X	
Noisiness	X									X	X	X		X						X	X			X	X				X	
Stumbled motor		X														X							X	X						
No fluid delivery	X							X	X								X		X	X				X	X			X		X
Uneven operation	X									X										X	X				X					X
Insufficient capacity	X							X	X	X		X	X		X			X	X	X	X	X		X	X			X		X
Overheated bearings	X		X	X		X					X									X				X					X	X
Raised fluid temperature	X	X										X								X				X			X	X	X	X
Raised motor temperature		X								X			X	X		X	X		X		X							X		X
Reduced bearing useful life	X	X		X	X	X	X				X					X						X								
Inadequate discharge pressure	X							X		X		X	X	X	X		X	X	X	X	X	X		X	X			X		X
Disproportionate power demand		X	X	X				X	X				X		X	X	X	X				X	X						X	
Reduced mechanical seal useful life	X	X	X	X	X	X	X				X					X										X			X	X

8.7.2 Rotary Pump

A rotary pump traps fluid in its closed casing and discharges a smooth flow. It can handle almost any liquid that does not contain hard and abrasive solids, including viscous liquids. This type of pumps is also simple in design and efficient in handling flow conditions that are usually considered too low for economic application of centrifugal pumps. Different sorts of rotary pumps include gear, lobular, screw, and vane pumps. To illustrate, in gear pumps the fluid is trapped by the opening between the gear teeth of two identical gears and the chasing of the pump on the suction side. On the pressure side the fluid is squeezed out when the teeth of the two gears are rotated against each other. The motor provides the drive for one gear. The lobular pumps operates similar to the gear pump, but with two lobes driven by external timing gears [456].

Rotary pumps find wide use for viscous liquids. When pumping highly viscous fluids, rotary pumps must be operated at reduced speeds because at higher speeds the liquid cannot flow into the casing fast enough to fill it. Unlike a centrifugal pump, the rotary design will deliver a capacity that is not greatly affected by pressure variations on either the suction or discharge ends. In services where large changes in pressure are anticipated, the rotary design should be considered [641].

A Rotary Vane Pump

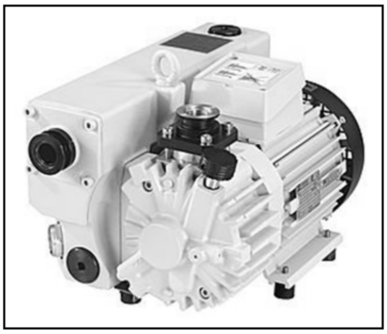


Figure 230 A picture showing a rotary vane vacuum pump [WS69]

Rotary pumps make up about 10% of the pumps used in industry. Unlike the more common centrifugal pumps which compose more than 80% of the industrial pumps they are able to deliver constant volume of liquid regardless of the pressure they encounter. Besides, for these pumps the discharge pressure is determined by resistance, and not affected by the specific gravity of the fluid [456]. Rotary pumps have many similar failure modes to the ones of centrifugal pumps [444]. They are susceptible to process induced failures resulted from excessive demands. The most common failure modes of rotary pumps are generally linked to the problems with the suction supply. These pumps should be supplied with constant volume of clean fluid to operate properly [54]. Table 74 represents a problem and cause analysis which has been carried out for rotary pumps.

Table 74 Problem and cause analysis of rotary pump

Object: Rotary Pump Cause Problem	Misalignment	Very low speed	Pump operated dry	Dirt or chips in fluid	Motor or driver failure	Very high fluid viscosity	Inadequate fluid supply	Binding rotating element	Internal component wear	Wrong rotational direction	Very high fluid temperature	Very high discharge pressure	Pipe pulling on pump's casing	Liquid vaporized in suction line	Blocked suction filter or strainer	Air leakage into piping or shaft seal	Stuck open or wrongly set relief valve	Suction piping not immersed in liquid
Vibration	X		X				X	X	X			X	X	X	X	X		
Noisiness	X		X				X	X	X			X	X	X	X	X		
Excessive wear	X		X	X			X	X				X	X					
Excessive heat	X		X					X					X					
Stumbled motor		X				X	X	X				X						
No fluid delivery			X		X				X	X					X			X
Insufficient capacity		X					X		X		X	X		X	X	X	X	
Raised fluid temperature						X						X		X				
Starting but loosing prime							X				X			X				X
Raised motor temperature	X					X		X		X			X		X	X		
Inadequate discharge pressure		X	X				X		X	X				X	X	X	X	X
Disproportionate power demand	X					X		X				X	X					

8.7.3 Reciprocating Pump

Reciprocating pumps consist of a power end and a liquid end. The power end of the pump takes the driver power and converts the rotary motion to reciprocating motion. The driver can be a motor, an engine, or a turbine whose output is then converted by means of crankshafts, connecting rods, and crossheads, to reciprocating motion [641].

These pumps can be single action or double action (i.e. pump provides pressure as the piston advances and as it retracts). Reciprocating pumps are ideal for providing short bursts of high pressure. In a reciprocating pump, a volume of liquid is drawn into the cylinder through the suction valve on the intake stroke and is discharged under positive pressure through the outlet valves on the discharge stroke. The discharge from a reciprocating pump is pulsating and changes only when the speed of the pump is changed. This is because the intake is always a constant volume. Often an air chamber is connected on the discharge side of the pump to provide a more even flow by evening out the pressure surges. Reciprocating pumps are often used for sludge and slurry. An older design or reciprocating pumps called the direct acting steam pump. This pump consists of a steam cylinder end in line with a liquid cylinder end, with a straight rod connection between the steam piston and the pump piston or plunger. These pistons are double acting which means that each side pumps on every stroke. Another construction style is the power pump which converts rotary motion to low speed reciprocating motion using a speed reducing gear [456].

A Reciprocating Pump

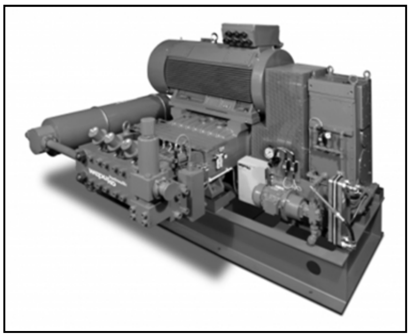


Figure 231 A picture representing a reciprocating pump [WS108]

In general, reciprocating pumps can endure more operational misuse and demand variations in comparison with centrifugal and rotary pumps. Nevertheless, similar to their rotary counterparts, they must have a constant supply of relatively clean liquid to operate properly. Indeed, due to close tolerances between the piston and cylinder walls, these pumps cannot bear contaminated fluid in their suction-supply system. Many of failure modes of reciprocating pumps are initiated by contamination, dirt and girt entering the suction side of the pump. Nonetheless, the most sensitive parts of these pumps are inlet and discharge valves which control the pumping action. Valve failure, which is usually caused by fatigue, is the most frequent source of these pumps failure [444]. Table 75 provides a problem and cause analysis performed for reciprocating pumps.

Table 75 Problem and cause analysis of reciprocating pump

Object: Reciprocating Pump Cause Problem	Overloads	Misalignment	No fluid supply	Cylinder failure	Unfilled cylinder	Broken valve springs	Excessive suction lift	Inappropriate packing	Inadequate lubrication	Wrong operational speed	Worn cross-head or guide	Loose internal component	Non-condensables in liquid	Rusted internal component	Inadequate suction pressure	Leaking relief or bypass valve	Very low volumetric efficiency	Abrasives or corrosives in fluid	Gear drive or drive-train failure	Stuck open or wrongly set valve	Blockade in lines or pump housing	Liquid entry into power end of pump	Worn valve, seat, liner, rod or plunger
Vibration		X			X	X			X				X	X					X		X		
Noisiness					X	X			X				X	X					X		X		
Stumbled motor	X	X							X				X						X		X		
No fluid delivery			X	X			X						X		X						X		X
Constant knocking												X		X					X				
Insufficient capacity				X	X	X	X			X			X		X	X	X			X			X
Excessive wear at fluid end					X	X												X					X
Reduced packing useful life		X			X			X			X		X				X	X					
Excessive heat at power end									X	X	X			X									
Excessive wear at power end	X													X									

8.8 Summary and Future development Potentials

The object based problem and cause analysis can only be effectively utilized if it is undertaken for all major machines and equipment and critical machine elements in a plant. After having such a comprehensive problem and cause analysis, it will be possible to determine the most common problems and causes in a plant and optimally modify the problem and cause lists in the information system of the plant. It is also then possible to ask technicians using OBPCA tables in providing feedbacks on the occurred failures. The seven machine groups or elements for which the problem and cause analysis has been undertaken throughout this chapter are just randomly chosen from a list of the most critical machineries in manufacturing and processing industry. The advantage of this tool can only be seen if it is frequently used in practice, and as mentioned above, this is not possible unless such OBPCA tables are developed for all critical machines and their components in a plant.

It is also essential to highlight that object based problem and cause analysis is completely different than root cause failure. Here, the problems and first level causes of those problems associated with a particular machinery object are identified and correlated. This is the most vital information which has to be included in any machinery failure report. The most of counter actions against the occurred and potential failures can be easily founded based on this information. Root cause failure analyses, although very helpful, but require incomparable amount of time and expert knowledge to be performed. This is indeed the reason why root cause failure analysis is considered to be unfeasible and impractical in many industries, whose operations are not extremely human and environment critical. In contrast, object based problem and cause analysis seems as a must for every manufacturing and processing plant just considering the numerous benefits and assistance it provides.

As a future research and development step, after doing a problem and cause analysis for every machinery object it will be wise and valuable to determine and include information like operation characteristics and requirements, best predictive, preventive and planned maintenance practices, routine inspection and maintenance procedures for that particular machinery object in a catalog. In other words, the next phase of any upcoming activity in this framework can be creating a catalog for every machinery object that comprises all analyses, operations and maintenance information, and expert knowledge about it. This will definitely help gathering and archiving all critical information the maintenance personnel need to deal with machinery failures. Obviously, like all the other tools of the CBM toolbox, the OBPCA tables or the mentioned catalogs can be developed in e-format as part of a plant’s information system or the CBM toolbox software.

9 Sample Application

Through the previous chapters different tools of the CBM toolbox are introduced and described extensively. The procedure of using the toolbox in practice is clear-cut. It starts with undertaking a statistical failure analysis of a facility, identifying its critical elements such as critical stations and machinery objects and their problems. Then after by use of the CMT/NDT knowledgebase, alternative methods and techniques to identify these associated problems are determined. Using the two decision making support tools, the financial analysis tool and selection matrix, the most appropriate method among all these alternatives is selected. Besides, with the help of object based problem and cause analysis, it is always tried to continuously increase the quality of the data which get into the information system of the plant. So that, in an iterative manner the reliability of the obtained solutions is increased. In this chapter the steps in using the CBM toolbox are shown more clearly with help of an example.

9.1 Use of the Statistical Failure Analysis

By undertaking the statistical failure analysis in the P1 facility, as shown in chapter 5, it can be easily seen that ‘wire’ is the most critical object based on the data recorded between 01.07.2005 and 30.06.2009 in the information system of the plant. In this period there were 148 problems associated with wires out of total 1216 problems linked to machinery objects. This number counts for 12.2% of total problems of machinery objects. In the same period, there has been 228 hours of repair and maintenance spent to abolish the wire problems and this puts wires in the second rank of R&M demanding machinery objects in the P1 facility (refer to figure 233). Such information helps maintenance manager determining the critical and most maintenance-demanding object(s) in a particular facility. Statistical failure analysis can provide plenty of valuable information about these objects and their associated problem and problem-causes as explained in chapter 5.

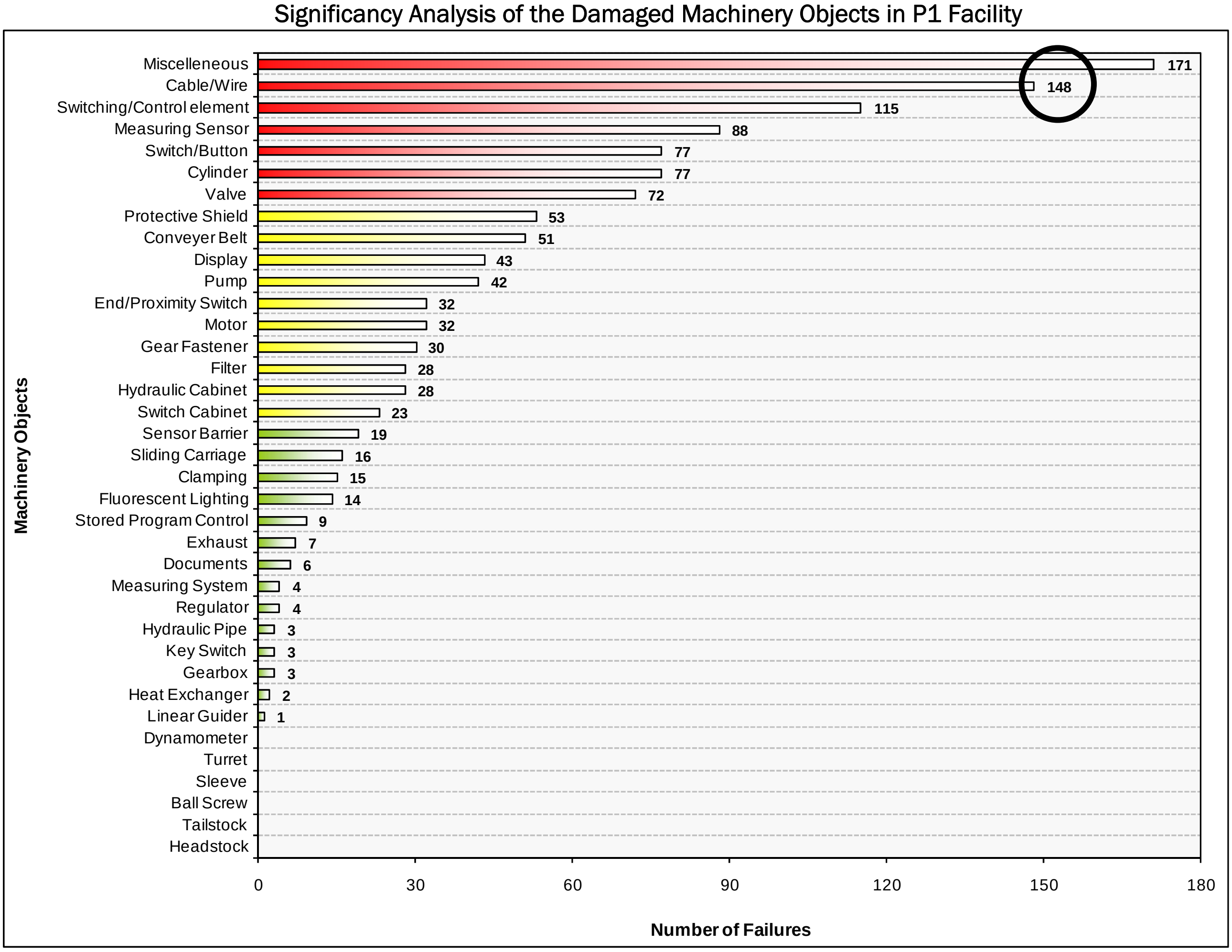


Figure 232 Number of damaged machinery objects in the P1 facility from 01.07.05 to 30.06.09; there is an approximate multi-colored classification of 60%, 30% and 10% of the total number of damaged objects.

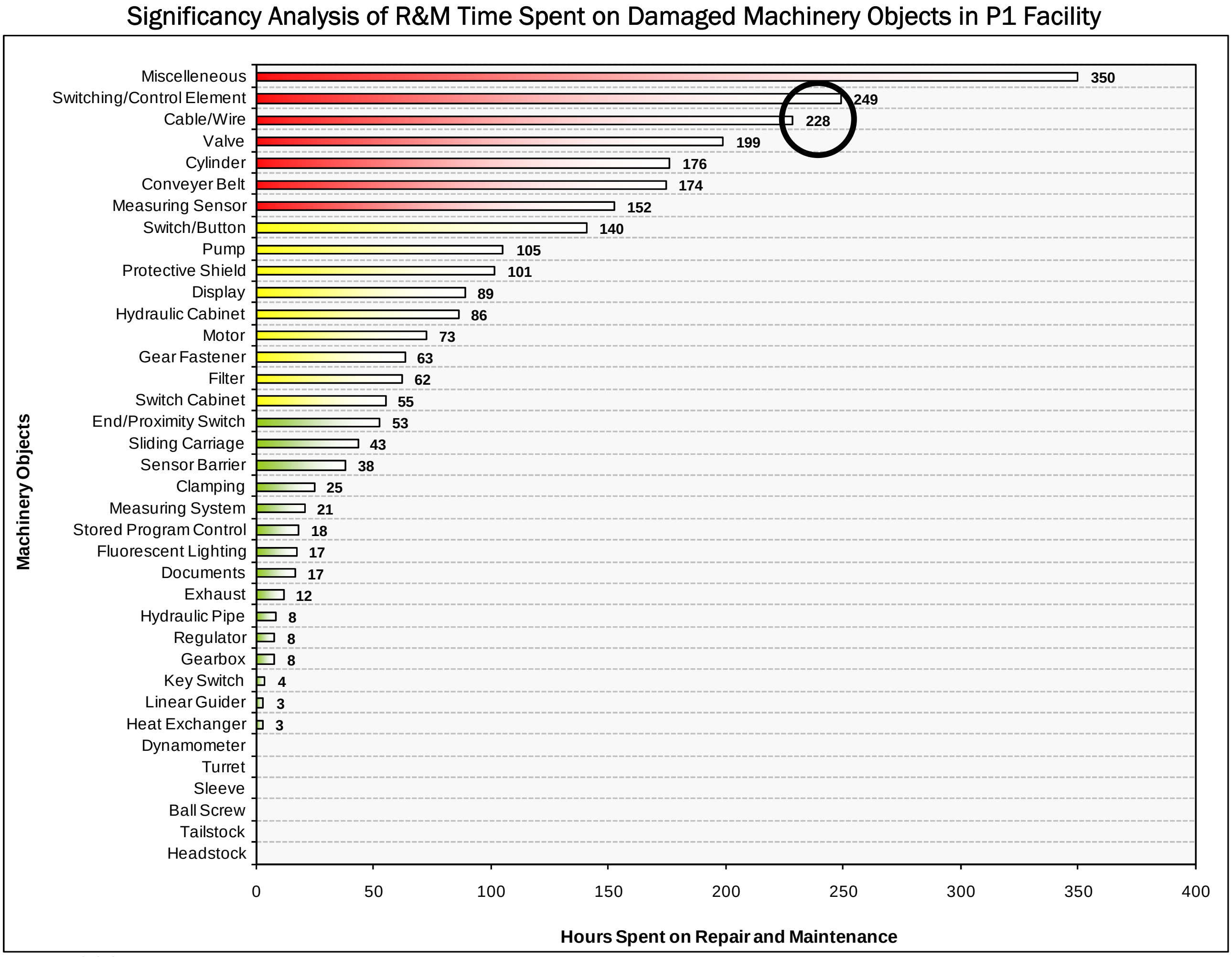


Figure 233 Number of hours spent on repair and maintenance of damaged machinery objects in the P1 facility from 01.07.05 to 30.06.09

Referring to table 6 in chapter 5, it can also be perceived that ‘wire’ has been the most failure-critical machinery object in the stations S05, S06, S07, S16 and S18 constituting 40%, 35.1%, 41.4%, 21.6%, 27.8% of total damaged objects in these stations respectively. So, where exactly the preventive maintenance work has to be initially focused is also known. Moreover, based on the information provided in table 11 in chapter 5, the main three problems that wires have shown to have in P1 facility were no function, partial damage, and isolation damage with corresponding 65, 29, and 8 reported problems. According to table 15 of the same chapter, the major three causes of these problems are abrasion, rupture and crash with 49, 34 and 4 occurrence respectively.

At this point, the importance of having meaningful, reliable and well-structured data in the information system of the plant reveals itself. If the problems and their causes are accurately known, it would be considerably easier to predict and identify them via suitable condition monitoring techniques and nondestructive tests; and thus, prevent and eliminate them via proper maintenance conducts. Previously, it has been argued that with having optimal problem and cause lists in the information system and with help of object based problem and cause analysis this objective can be achieved.

Statistical failure analysis can provide the practitioners with other supplementary information as well. For instance, from the graphs in the next page it can be easily recognized that most of the problems associated with wires occur in March and September. Expectedly, most of the repair and maintenance hours spent in March and September in addition to November and December. This basically shows that most of the maintenance undertaken has been either in form of reactive to the occurred problems or in the form of inappropriately planned maintenance. The best practice would be to undertake preventive maintenance activities in the months prior to the peak months of failures, i.e. February and July. In chapter 5 all resultant information, their benefits, and other potentials of statistical failure analysis are extensively explained and highlighted.

Monthly Variation of the Damaged Machinery Objects in P1 Facility

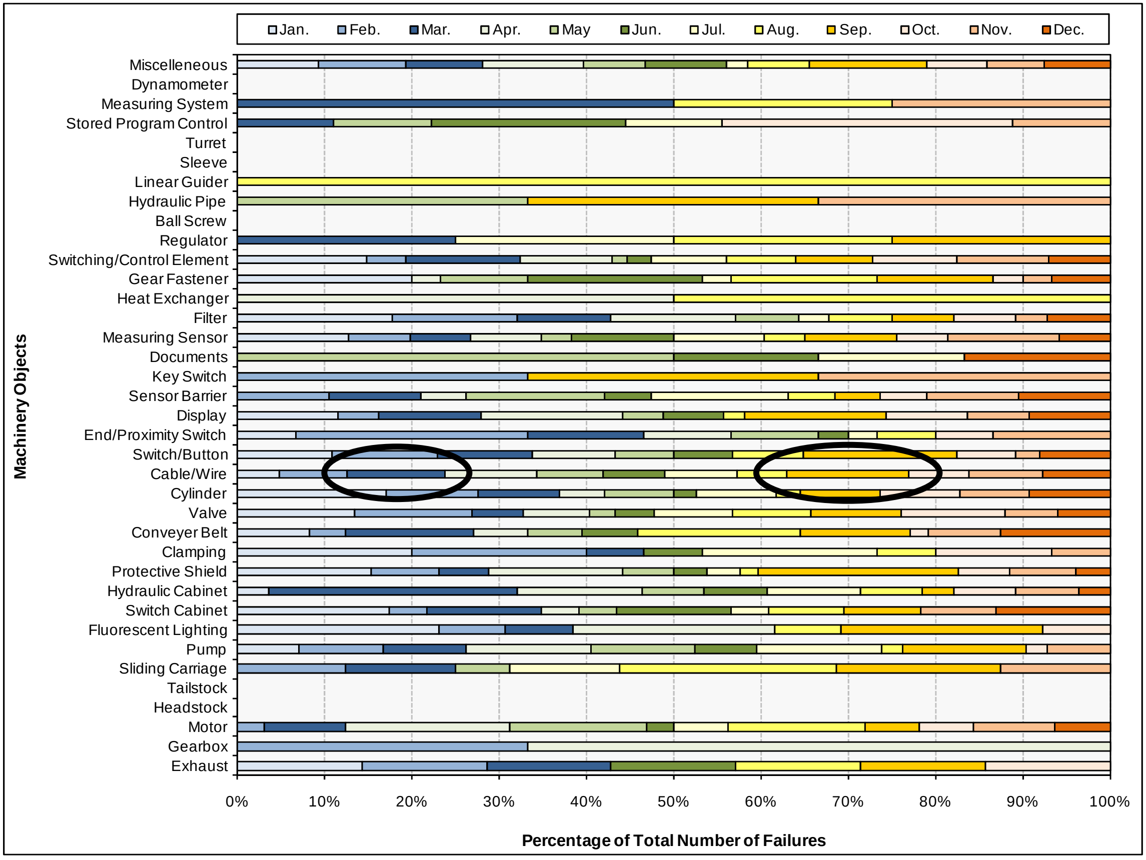


Figure 234 Percentage of damaged machinery objects in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

Monthly Variation of R&M Time Spent on Damaged Machinery Objects in P1 Facility

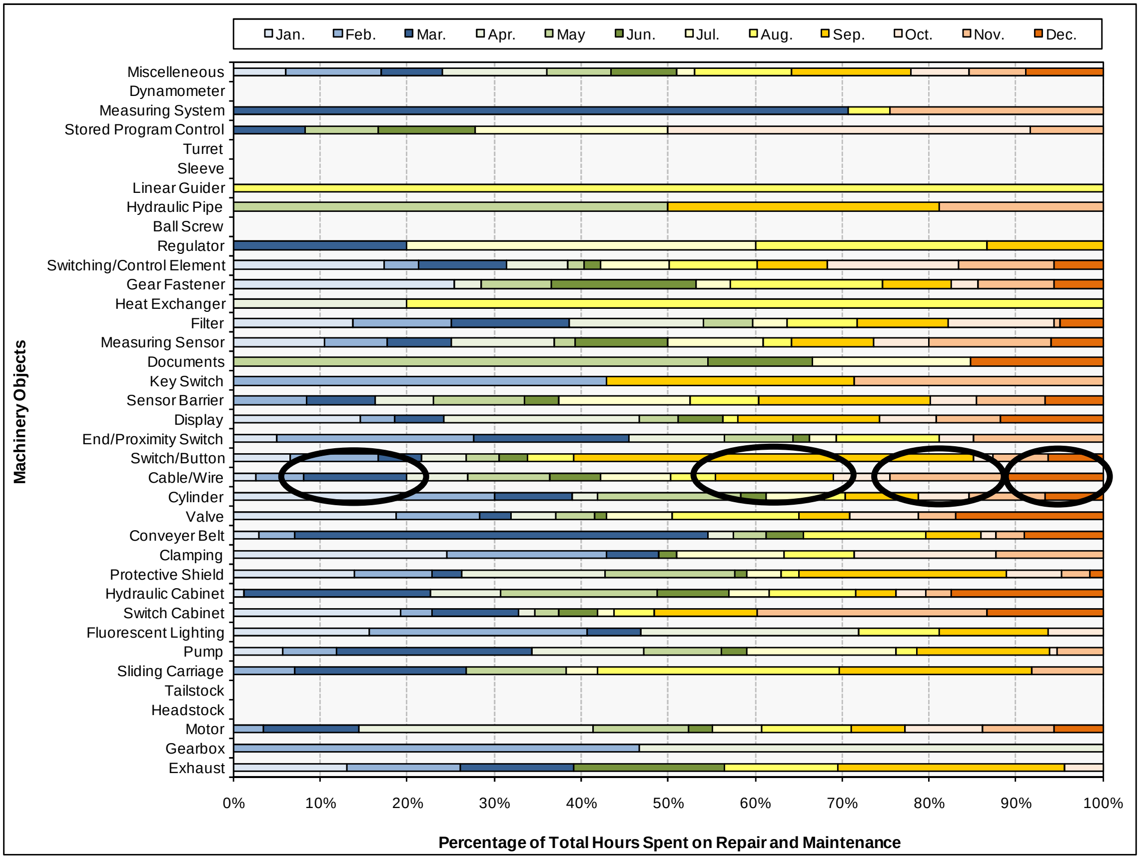
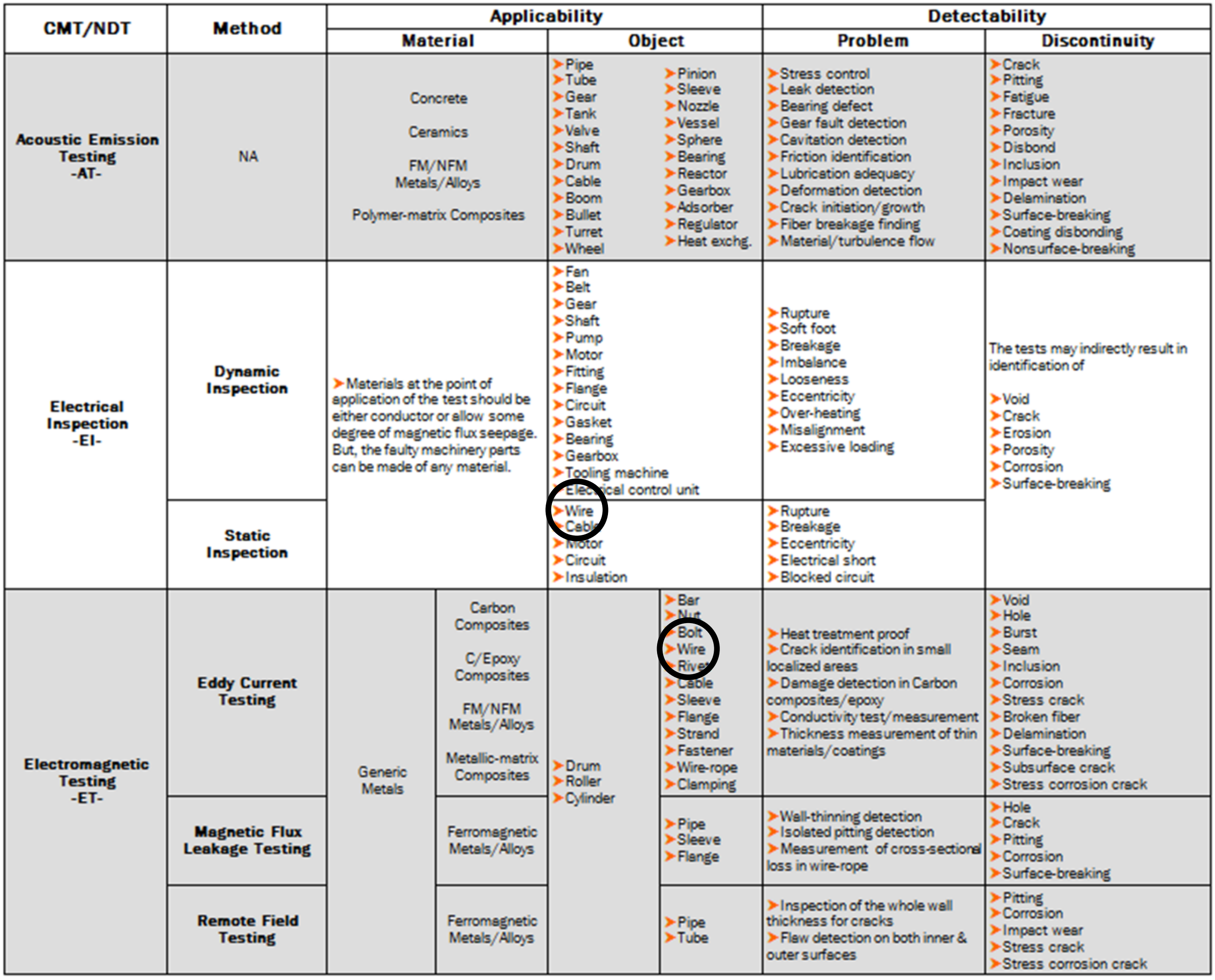


Figure 235 Percentage of total hours spent on repair and maintenance of damaged machinery objects in the P1 facility with respect to the month of occurrence from 01.07.05 to 30.06.09

9.2 Use of the CMT/NDT Knowledgebase

Determining the critical object, its associated problems and their causes in addition to know where the preventive maintenance activities have to be initiated (i.e. in which station), the next step is to figure out which CMT or NDT is the most applicable and appropriate one to be used. This is done with the help of the CMT/NDT knowledgebase. Going through the provided expert knowledge in the knowledgebase, particularly with help of the all-embracing tables of Appendix D, and searching for the wire as the sought object, it can be easily found out that there are three major condition monitoring techniques which may be used to foresee and prevent various problems of wires. These are namely electrical inspection (static inspection method), electromagnetic testing (eddy current testing method), and visual/optical inspection (eye-mirror-flashlight method). As explained, it must be clear that if there is more concrete information about the exact problems of the wires rather than general terms such as no function, the CMT/NDT knowledgebase can provide more explicit answers.

A Partial Snapshot of the ADAD Table



CMT/NDT	Method	Applicability		Detectability	
		Material	Object	Problem	Discontinuity
Acoustic Emission Testing -AT-	NA	Concrete Ceramics FM/NFM Metals/Alloys Polymer-matrix Composites	Pipe Tube Gear Tank Valve Shaft Drum Cable Boom Bullet Turret Wheel Pinion Sleeve Nozzle Vessel Sphere Bearing Reactor Gearbox Adsorber Regulator Heat exchg.	Stress control Leak detection Bearing defect Gear fault detection Cavitation detection Friction identification Lubrication adequacy Deformation detection Crack initiation/growth Fiber breakage finding Material/turbulence flow	Crack Pitting Fatigue Fracture Porosity Disbond Inclusion Impact wear Delamination Surface-breaking Coating disbonding Nonsurface-breaking
Electrical Inspection -EI-	**Dynamic Inspection**	Materials at the point of application of the test should be either conductor or allow some degree of magnetic flux seepage. But, the faulty machinery parts can be made of any material.	Fan Belt Gear Shaft Pump Motor Fitting Flange Circuit Gasket Bearing Gearbox Tooling machine Electrical control unit	Rupture Soft foot Breakage Imbalance Looseness Eccentricity Over-heating Misalignment Excessive loading	The tests may indirectly result in identification of Void Crack Erosion Porosity Corrosion Surface-breaking
	Static Inspection		Wire Cable Motor Circuit Insulation	Rupture Breakage Eccentricity Electrical short Blocked circuit	
Electromagnetic Testing -ET-	**Eddy Current Testing**	Generic Metals Carbon Composites C/Epoxy Composites FM/NFM Metals/Alloys Metallic-matrix Composites	Drum Roller Cylinder Bar Nut Bolt Wire Rivet Cable Sleeve Flange Strand Fastener Wire-rope Clamping	Heat treatment proof Crack identification in small localized areas Damage detection in Carbon composites/epoxy Conductivity test/measurement Thickness measurement of thin materials/coatings	Void Hole Burst Seam Inclusion Corrosion Stress crack Broken fiber Delamination Surface-breaking Subsurface crack Stress corrosion crack
	Magnetic Flux Leakage Testing	Ferromagnetic Metals/Alloys	Pipe Sleeve Flange	Wall-thinning detection Isolated pitting detection Measurement of cross-sectional loss in wire-rope	Hole Crack Pitting Corrosion Surface-breaking
	Remote Field Testing	Ferromagnetic Metals/Alloys	Pipe Tube	Inspection of the whole wall thickness for cracks Flaw detection on both inner & outer surfaces	Pitting Corrosion Impact wear Stress crack Stress corrosion crack

Figure 236 A partial snapshot of the ADAD table which provides an overview of applicability, detectability, advantages and disadvantages of various CMTs/NDTs

Each of these tests has its own advantages and disadvantage in addition to exact applicability. A maintenance professional may review such information in the CMT/NDT knowledgebase and choose the more applicable ones taking into account the technical and business related factors which are important in his company. Nevertheless, there is usually more than one condition monitoring technique or nondestructive test which can be used in a particular case. Therefore, there should be some tools to support making the most correct decision by considering all different aspects from finance to safety and even environmental issues. This is done with the help of two decision support tools which take into account all of these aspects and provide a single answer to the question of which test or technique has to be used. The chosen test is the most appropriate one for a specific case in a particular company.

9.3 Use of the Decision Support Tools

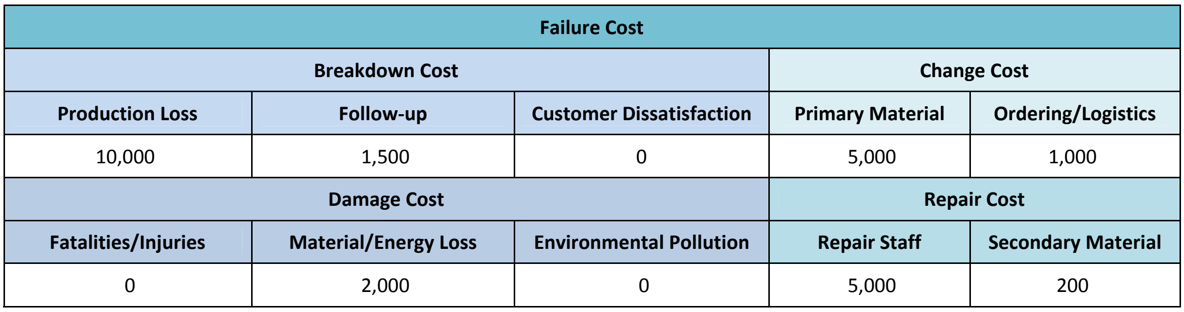
Knowing that the three alternative techniques applicable for condition based maintenance of wires are EI (static inspection method), ET (eddy current testing method), and VI (eye-mirror-flashlight method), the next step is to determine which one is the most appropriate one to be used in a particular case (i.e. in a particular company and for a specific facility). For this purpose, there exist two decision support tools: the financial analysis tool and CMT/NDT selection matrix.

To illustrate how these tools work, a sample simulation can be provided. It is essential to underline that the undertaken simulation is based on assumed factors such as breakdown cost or the importance of technology compatibility for the company. Clearly, in reality one can just plug the actual numbers and parameters retrieved from the information system or obtained from the management committee of the company and get use of these tools based on real data.

As it has been explained before, due to substantial initial investments and particular training required, cost of running a condition monitoring technique or a nondestructive test is considerable; hence, there must be huge recompense to be gained in minimizing the amount of corrective or planned maintenance that is used to be performed and maximizing the CBM related activities. In other words, any CMT/NDT employed should be financially feasible and have more monetary benefits in comparison with others. To quantitatively identify a test's feasibly the financial analysis tool is used.

The first step towards undertaking a financial analysis using this tool is to calculate and/or estimate all costs associated with failure of a particular object (e.g. wires) or occurrence of a certain problem in a facility. These costs are known to be the breakdown cost, change cost, damage cost and the repair cost, each of which consisted of some subclasses of costs as shown in figure 237. The exact definitions and descriptions of these costs are provided in chapter 7. For the case of the damaged wires in P1 facility with 148 reported failures and 228 R&M hours spent on them in four anni, the following failure costs are guesstimated for one year.

A Partial Snapshot of the CMT/NDT Financial Analysis Tool - Failure Cost



Failure Cost				
Breakdown Cost			Change Cost	
Production Loss	Follow-up	Customer Dissatisfaction	Primary Material	Ordering/Logistics
10,000	1,500	0	5,000	1,000
Damage Cost			Repair Cost	
Fatalities/Injuries	Material/Energy Loss	Environmental Pollution	Repair Staff	Secondary Material
0	2,000	0	5,000	200

Figure 237 A partial snapshot of the financial analysis tool indicating the assumed/estimated costs associated with failures of wires in the P1 facility in one year. All the costs are in Euro.

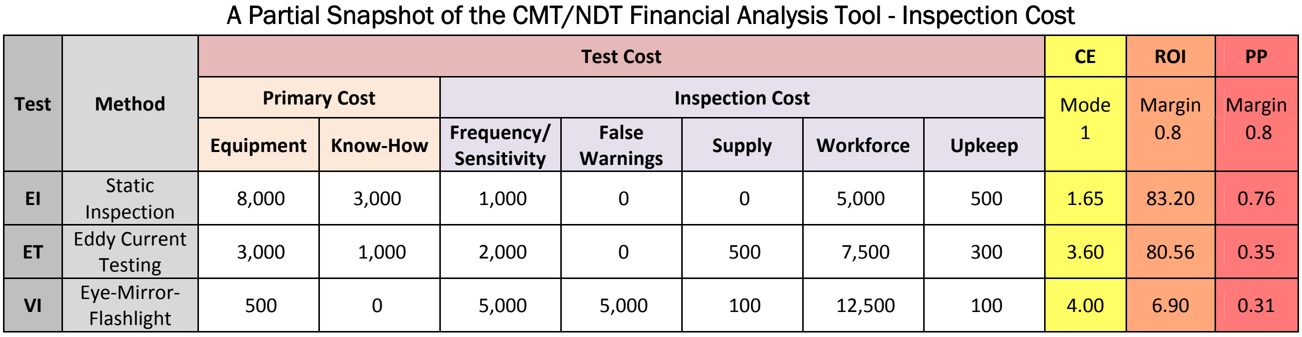
The cost of production loss is roughly estimated considering the total R&M hours spent to fix the wire problems in relation to the total hours available for production in year. In reality this figure can be exactly determined by retrieving related information from the ERP system of the plant. The follow-up cost is related to any delay or modification of planned production or other activities due to the occurred break down. Aside from approximations, it can be calculated based on the man-hours spent to modify the production plans or take necessary follow-up actions. Cost of customer dissatisfaction is estimated based on the long-term data extracted from different sources in the company. Here, it is considered to be negligible and thus its value is set to zero.

As there has been no fatalities or injuries reported due to failures of wires in the plant this cost is set to zero. Cost of material and energy loss is more of a hidden source of expense which is usually ignored in industry although it is of considerable importance. This can be guesstimated as a percentage of the production loss or can be more exactly estimated if there are necessary tools available. There has not been any incurred expense due to environmental pollution caused by failure of wires in this plant. However, in some industries like pharmaceuticals, chemicals or petroleum such a cost can be huge. In chapter 7, it has been briefly explained how to calculate the cost of customer dissatisfaction.

Change cost is more straightforward and can be directly calculated according to the available maintenance and repair data in the information system of the plant. This involves both cost of the material which has to be replaced or repaired and cost of the ordering, purchasing or commissioning that material, which can be approximated as a percentage of the former element, i.e. cost of required primary material. Last but not least is the cost of repair which is consisted of the wage of the repair staff employed or appointed to fix the problem and the cost associated with any secondary material required to carry out the repair (e.g. glue). The exact numbers can be calculated based on the maintenance and repair orders and confirmation reports in the information system.

The second major step is to identify or estimate the costs associated with the tests to be compared. These include the initial cost of purchasing necessary hardware as well as training personal and bringing the know-how to the plant. Plus, cost of inspection on an annual basis which is relatively more complex to be calculated as it is consisted of various components such as the frequency of inspection and its degree of sensitivity, possible false alarm or warnings, material and workforce required to run the inspection and finally the maintenance cost of the inspection equipment themselves.

These costs can be exactly identified by asking the companies which produce the tests equipment and provide the inspection services. Besides, some estimation can be provided by the experienced technicians in the plant or various information sources in the internet. Having these costs as exact numbers or rough estimation and plugging them in the financial analysis tool the cost effectiveness, return on investment and payback period of the tests to be compared are calculated. For CE, mode defines if the results are shown in percentage format or as ratios. For ROI and PP, margin is indeed a scope of realization as whatever test and technique is employed to prevent a particular type of failure, it would only be able to partially predict and eliminate the existing problems.



A Partial Snapshot of the CMT/NDT Financial Analysis Tool - Inspection Cost

Test	Method	Test Cost							CE	ROI	PP
		Primary Cost		Inspection Cost					Mode 1	Margin 0.8	Margin 0.8
		Equipment	Know-How	Frequency/ Sensitivity	False Warnings	Supply	Workforce	Upkeep			
EI	Static Inspection	8,000	3,000	1,000	0	0	5,000	500	1.65	83.20	0.76
ET	Eddy Current Testing	3,000	1,000	2,000	0	500	7,500	300	3.60	80.56	0.35
VI	Eye-Mirror-Flashlight	500	0	5,000	5,000	100	12,500	100	4.00	6.90	0.31

Figure 238 A partial snapshot of the financial analysis tool indicating the assumed/estimated costs associated with inspection of wires in the P1 facility in one year using EI, ET and VI methods. All the costs are in Euro.

It is essential to explain that static inspection is a nonintrusive test which requires various tools or an all-in-one advance device and considerable training. On the other hand, it does not need to be undertaken very frequently. It provides precise results and thus there is no possibility of having false warnings and just a trained technician can undertake the test. Eddy current equipment is cheaper and needs less training in comparison. It also provides reliable results though the test has to be carried out more frequently so it demands higher man-hour. Visual inspection via eye-mirror-flashlight method is very simple and cheap. It basically needs no special training. However, such inspections should be done often and even so VI is not able to identify many problems at preliminary phases of development, specially, when problems are concealed by the insulation. Thus, this method is not very reliable. Meanwhile, it needs many technicians to walk around and check the wires, i.e. it requires considerable man-hours in comparison with the other two tests.

According to figure 238, all tests have a payback period less than a year with VI leading. Static inspection has the highest return on investment while eye-mirror-flashlight has the least due its inability to identify different problems and less reliability. Eddy current testing has considerable cost effectiveness while maintaining a relatively short payback period. Nevertheless, just by calculating and taking into account these financial indicators it is not possible to choose the most appropriate test among the alternatives. There are plenty of other factors to be considered and analyzed. These factors reflect wide range of aspects from usability to safety. To have a systematic analysis of these factors and make a comprehensive decision about the most appropriate test the CMT/NDT selection matrix is used.

The CMT/NDT selection matrix reflects the degree of usability, feasibility, efficacy, compatibility and safety of the alternative tests to be compared and calculates a factor called UFECS. This factor provides an overall assessment of the importance of all the mentioned elements mulling over the importance of these elements from the company's perspective. The test which has the highest UFECS factor is the most appropriate one to be used for a certain case in a particular company. In this case, static inspection, eddy current testing and eye-mirror-flashlight are to be compared. The exact definitions and descriptions of the UFECS elements and their sub elements are inclusively explained in chapter 7.

To use the selection matrix, a ranking level from 1 to 5 is given to each element or criterion for each test. In addition, a weight is allocated to each element denoting the importance of that specific element for the company, based on the company's overall strategy, business policy, financial condition, type of the already utilized technology in the plant (e.g. operating systems, hardware), importance and allowable/regulated degree of safety in the plant, and so on. The weight can intake an incremental value from 0 to 1 representing 0 to 100% significancy of a particular element for the company. In the below figure, such an assessment is simulated for selecting the most appropriate test among static inspection, eddy current testing and eye-mirror-flashlight inspection for condition monitoring and testing the wires in the P1 facility.

A Snapshot of the CMT/NDT Selection Matrix

Test	Method	Usability			Feasibility			Efficacy					Compatibility					Safety		UFECS Factor
		Applicability	Availability	Transferability	Cost	Manageability	Time	Sensitivity	Accuracy	Reliability	Robustness	Practicality	Instrumentation	Operating System	Communication	Know-how	Incidence	Personnel	Environment	
		Weight 1	Weight 0.75	Weight 0.75	Weight 0.5	Weight 0.5	Weight 0.25	Weight 0.25	Weight 0.75	Weight 0.75	Weight 0.5	Weight 1	Weight 0.25	Weight 0.25	Weight 0.75	Weight 0.5	Weight 0.5	Weight 0.75	Weight 0.75	
EI	Static Inspection	5	4	3	2	3	3	4	4	4	3	4	3	3	4	2	3	5	5	40.50
ET	Eddy Current Testing	4	5	4	3	4	4	4	3	3	2	3	4	3	3	3	3	5	5	39.25
VI	Eye-Mirror-Flashlight	2	5	5	5	5	4	1	1	1	5	5	5	5	2	5	1	4	5	38.50

Figure 239 A snapshot of the selection matrix indicating the allocated weights and ranks associated with various criteria regarding EI, ET and VI methods in the P1 facility.

As figure 239 indicates, all the three compared tests have UFECS factors close to each other. Nevertheless, static inspection with a UFECS factor of 40.50 seems to be most appropriate test for condition based maintenance of wires in the P1 facility. It is vital to express that such a solution is obtained based on the data derived from the plant's information system, undertaken statistical analysis and many rough estimations and assumptions. In this chapter the aim was to show how the created systematics and the CBM toolbox work.

It must be clear that with higher quality data (i.e. longer time length, more exactness, and higher reliability) and exact calculations rather than approximations or guesstimates, superior results will be achieved. For example, knowing exactly what exact type of wires are of concern, what problems made these wires failed and what were the causes, can help choosing the most applicable tests and techniques from the CMT/NDT knowledgebase. Besides, calculating the associated costs of failures and attaining accurate information about the costs of running each test result in more reliable solutions.

9.4 Use of the Object Based Problem and Cause Analysis

Through this chapter, it has been shown how the CBM toolbox can be utilized in practice. It has been also underlined that having more accurate data about the exact problem and cause which made an object failed is the first and foremost step towards achieving more reliable results. To assist the maintenance technicians with providing higher quality data, the third major tool in the toolbox has been introduced. In object based problem and cause analysis, all possible problems of a machinery object or equipment are identified, the most common problems are chosen, the probable causes of these problems are determined, and eventually the problems and causes of these problems are correlated in a comprehendible way.

When a failure occurs, the technician who is appointed to fix the problem uses just a table to provide exact data with a common language in the information system of the plant. If the problem or its cause does not exist in the table, the table is updated accordingly. The information required to undertake such an analysis and make an OBPCA table can be retrieved from various sources such as talks with experts and technical articles and books. To continue with the example of wires in the P1 facility, such an analysis has been undertaken and an OBPCA table has been made. Table 76 represents a problem and cause analysis which has been carried out for wires in general.

Table 76 Sample problem and cause analysis of wire

Object: Wire Cause Problem	Corrosion	Delamination	Over bending	Loose terminal	Very tight clamp	Insulation crack	Loose connection	Dirt in connection	Incorrect splice size	Incorrect installation	Loose/incorrect crimp	Inappropriate wire type	Defective manufacturing	Deterioration of insulation	Worn/cut inside conductor	Inappropriate wire material	Excessive intermittent stress	Close wires with different voltages	Direct connection to other structures
Burnt wire						X					X			X			X		
Overheating	X				X			X				X				X			
Series arcing	X			X				X			X								
Parallel arcing																		X	X
Excessive wear	X					X			X					X			X		
Open wire failure															X				
Electrical shorting		X				X				X				X					
Insulation damage		X	X		X				X				X	X			X		
Reduced useful life			X		X				X	X		X				X	X		
Lower power delivery	X			X				X			X		X		X	X			
No electricity conveyance				X			X				X				X				

10 Summary and Prospect

Nondestructive testing and condition monitoring are considered to be the essential elements of condition based maintenance programs to manage physical assets of plants. Integration of different CMTs/NDTs and CBM is aimed not only to maximize but also to optimize the effectiveness of inspection and trouncing deficiencies of planned maintenance activities in addition to the machinery and equipment themselves. This incorporates different noninvasive tests and techniques to inspect or monitor machinery condition [663]. Certainly, it is highly beneficial to utilize and implement other CBM tools in parallel. The use of a condition based approach to maintenance can result in reduction of unwanted maintenance efforts in addition to justified and cost effective maintenance actions [65]. When CMT/NDT related data on flaw or crack size is combined with information on material properties, the operating environment, and flaw initiation and growth rates, a specialist can calculate a probability of failure for the component [615]. Moreover, this information can be converted into a remaining life estimate, if the future operating pattern can be supplied. The probability of failure can then be used to make run/repair/replace decision for that component based on the predicted cost of failure.

From time to time, the CMT/NDT method and procedure to be used for a specific machinery part or component is specified in manufacturer's maintenance or overhaul manuals. However, for many objects and equipment this does not hold true, thus, one has to have a broad knowledge of variety of CMT/NDT methods to be able to use the appropriate ones. The appropriate CMT/NDT method may consist of several separate inspections and monitoring. An initial inspection or preliminary monitoring may indicate the presence of a possible fault or defect, but other inspections may be required to confirm the original indication. Undertaking the correct CMT/NDT method selection requires an understanding of the basic principles, limitations, advantages and disadvantages of the available test and techniques and an understanding of their comparative effectiveness and cost. Keeping all these in mind, the significance of developing a CMT/NDT knowledgebase, in which the applicability, detectability, advantages and disadvantages of a wide variety of test are considered reveals itself. Nevertheless, to be able to make precise decisions supplementary tools such as CMT/NDT selection matrix and financial analysis have been designed and developed by the author.

However, just having such a knowledgebase is not sufficient to run a competent condition based maintenance program. Use of its filled expert knowledge has to be in parallel with adequate high quality and reliable information that can be obtained through other analyses. In fact, within the concept of condition based maintenance there exist two other essential tools that can be perfectly matched and put inside a toolbox along with the mentioned database. These are statistical failure analysis (SFA) and object based problem and cause analysis (OBPCA). Having all of these tools together and using them in joint and simultaneously, enormous amount of priceless benefits will be achieved. This is due to the combination of expert knowledge with statistical data and qualitative information attainable form the CMT/NDT knowledgebase, SFA and OBPCA accordingly. Therefore, based on all said and done, these tools are chosen to be exclusively configured and placed in a toolbox that can be effectively used with aim of sustaining a unique condition based maintenance program. Design, configuration and organization of such a CBM toolbox have been the focal concerns of this doctoral research project.

10.1 Review of the CBM Toolbox

As it has been previously emphasized, the target of this doctoral research project is to pioneer a specially configured toolbox that can be effectively used within the framework of condition based maintenance. The CBM toolbox contains three different but interrelated analyses as its tools: (1) the statistical failure analysis (SFA) and its resultant graphical information, proficient use of which brings about a statistical failure overview in the plant based on which maintenance efforts and activities can be properly focused and effectively evaluated. (2) The CMT/NDT analysis and its follow-on knowledgebase, skillful use of which results in an optimized nondestructive inspection and condition monitoring program according to the state-of-the-art and best industrial practices. (3) The object based problem and cause analysis (OBPSA) and its related graphical or tabulated catalogs, which facilitates achievement and visualization of an optimal problem and cause classification associated with particular object categories that can be used for better comprehension of machinery failures and continuous improvement of the information quality in a recapitulative and evolutionary manner.

In addition to these three major tools, there are two decision support tools integrated in the toolbox which provide the practitioners with the ease of choosing the most appropriate condition monitoring technique or nondestructive test for a particular case. In fact, because of significant initial investments and particular training and skill required, cost of running a CMT/NDT is substantial; hence, there must be huge reimburse to be obtained in minimizing the amount of corrective or planned maintenance that is used to be performed and maximizing the CBM-related activities. Moreover, this must be balanced against the risks of machinery failure and the consequences of failure which are potentially very undesirable. For this reason, a compact financial analysis tool has been developed to analyze each test from financial perspective. The compact financial tool calculates (1) cost effectiveness, (2) return on investment, and (3) payback period for each test or technique.

The CMT/NDT selection matrix is another tool designed to standardize and alleviate the decision making process in selecting the most appropriate CMT/NDT for a particular case in a plant. This tool, evaluates the overall effect of different criteria that are central to decide on the most suitable test or technique to be used to prevent a certain type of problem. These criteria, which were clearly defined in chapter 7, include usability, feasibility, efficacy, compatibility, and safety. The selection matrix incorporates a special weighting and ranking system based on which a final factor called “UFECS” is calculated. Among all available alternatives, the test with the largest UFECS factor will be the most appropriate one to be used for a specific case in a particular company.

The CBM Toolbox Overview

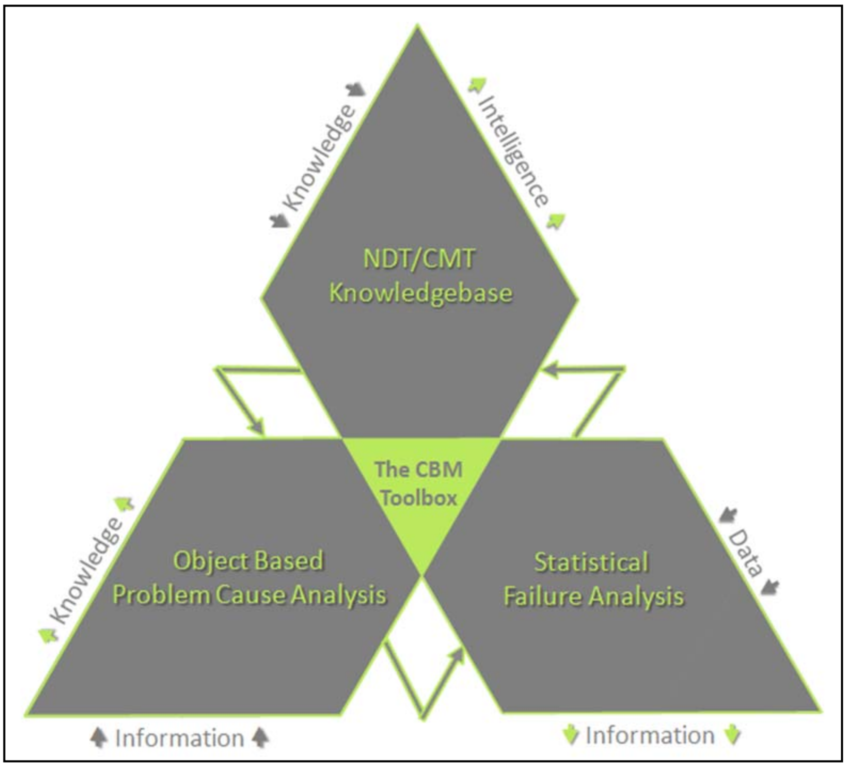


Figure 240 An overview of the structure and the information flows of the CBM toolbox

10.2 Concluding Remarks

It is beneficial to clear that some of the intermediate information provided by each CBM tool is used to improve or conclude the other ones and this happens in a progressive fashion supporting continuous improvement. To illustrate, one can consider the followings: The tabulated lists generated through OBPCA can be used to improve the problem and cause lists in the information system which is used by technicians to generate the data required for SFA and, thus, improve of which results in a better SFA. In time, some extra information about new problems or discovered causes given in the information system (by plant technicians) plus the expert knowledge attained through building the CMT/NDT knowledgebase can be used to develop the OBPCA lists more and more. The high quality information obtained from the improved SFA in joint with the knowledge will result in an effectively-run condition based maintenance program.

Indeed, there are two different information flows related to the CBM toolbox. There is an external information flow, via which particular data, information and knowledge come to the mentioned segments of the toolbox and the generated information, knowledge and intelligence go out. There exists also an internal information flow, through which the generated outcomes of each segment is either directly used by another one or indirectly affect the quality and accuracy of the outcomes being generated by other tools. To be more precise, in the first segment of the toolbox failure and maintenance related data available in the information system of the company (e.g. SAP system) is taken out and effectively analyzed to craft comprehensible information, interpretation of which is not only used to rise and solve maintenance related issues but also it is utilized to assist the management with enlightening various managerial concerns (e.g. from spare part and inventory management to performance evaluation of undertaken activities). In the second segment, large amount of expert knowledge from a wide range of sources are gathered and formatted in a way to create higher quality knowledge which is easier to be used and understood, or in other words, intelligence. In the third segment, the information associated with potential failure modes of different machinery objects and their probable causes is collected from diverse sources and tabulated in a handy way to produce intensive knowledge about object based failure modes and causes.

Coming to the internal information flow of the toolbox, the knowledge generated by the third segment, OBPCA, helps enhancing the quality, accuracy and reliability of the data generated in the information system of the company which is used by the first segment or SFA. Higher the quality and reliability of the data coming to the SFA results in higher quality and reliability of the information it generates. With reliable information in hand from SFA (e.g. the information about the most critical machinery part in a station and the most frequent problem associated with it), one refers to the second segment, CMT/NDT knowledgebase, and finds the most appropriate solution to predict and prevent a particular problem. The knowledge gathered in the first and second segments which is constantly updated by professionals, is also used to revise and renew the information in the third segment (e.g. recently discovered failure modes and causes). Hence, in this way the internal information flow of the CBM toolbox is closed as an inner loop. This is how the conception of continuous improvement is integrated with the function of the CBM toolbox which sustains its up-to-date content and conserves its superior functionality.

10.3 Summary of Contributions

The research outcome of this doctoral research project is an innovative condition based maintenance toolbox, the tools of which are different analyses. The blend of these analyses and their inter-connectivity for intermediate information flow in addition to precious resultant information provided by them are its remarkable features. As the research foundation, a knowledgebase has been developed involving extensive expert knowledge which is classified according to the applicability, detectability, advantages and disadvantages of different condition monitoring techniques and nondestructive tests. The CMT/NDT knowledgebase is jointly used with two other tools, statistical failure analysis and object based problem and cause analysis.

The use of the CBM toolbox in different manufacturing and processing industries has its own merits depending on how and what-for it is exactly utilized underlining that the toolbox as a whole endeavors to sustain an effective CBM program. However, every individual tool responds to particular issues and provides specific benefits which can be summarized below. For more details one shall review the corresponding chapters. For instance, use of the statistical failure analysis can bring about concrete answers to the following questions not only in a usual numerical way but also in a graphical manner which ease the understanding and interpretation of the content information:

- What are the attributes of major and minor failures?
- What are the most failure-critical stations of a facility?
- What are the failure characteristics of a machine/station/facility?
- How frequent particular failure modes occur in a station/facility/plant?
- How frequent particular failure causes occur in a station/facility/plant?
- What is the criticality status of different objects in a station/facility/plant?
- What are the most critical objects or machinery parts in a station/facility/plant?
- Which particular causes more instigate certain failures in a station/facility/plant?
- How much time has been spent to fix particular machinery items or to overcome certain problems?

The mentioned questions and the provided answers would engender concerns about other issues, investigating of which will definitely contribute in finding the grounds for failures and improving the overall maintenance and production activities. Use of such statistical failure analysis and the generated information and arose concerns will bring some resultant benefits which can be briefly listed as:

- Revealing the pitfalls of the information system
- Exposure of the mistakes of information providers
- Disclosure of failures attributes and characteristics
- Reasoning why particular causes more instigate certain failures
- Identification of the most critical machines in a station/facility/plant
- Identification of the most critical stations of a facility, or facilities of a plant
- Illustration of the vital issues regarding the machinery failure characteristics
- Measuring performance of overall maintenance activities if SFA is undertaken periodically

The second major tool, the CMT/NDT knowledgebase along with the two decision making support tools (financial analysis tool and selection matrix) facilitate the maintenance personnel with lucid, literal and precise answers to the subsequent questions:

- Which CMT/NDT is proper for which material?
- Which CMT/NDT is suitable for which machinery object?
- Which failure mode can be recognized by which CMT/NDT?
- Which discontinuity type can be identified by which CMT/NDT?
- Are CMTs/NDTs employed in the company properly chosen and as many as necessary?
- Which CMT/NDT technique is mostly feasible and appropriate to be used for a particular case?
- What are the possible technical improvements that can support/enhance the current CBM program?

Utilizing the CMT/NDT knowledgebase for everyday maintenance activities and having the answers of the above questions from a reliable source bring various resultant benefits for any maintenance department. These benefits can be briefly expressed as:

- Effective assessment of machinery condition
- Appropriate use of various CMTs/NDTs in the plant
- Justified and cost-effective condition based maintenance actions
- Reduction of unnecessary reactive and planned maintenance activities
- Unfailing prediction and prevention of different potential failures in advance
- Estimation of machinery remaining life-time if the information is joint with failure data history
- Reasonable in-sourcing or out-sourcing of condition monitoring and nondestructive inspections

Coming to the third major tool, employing the object based problem and cause analysis and generating the related graphical or tabulated catalogs help answering the below questions:

- What are common or potential problems associated with an object?
- What are common or potential causes of these frequent problems?

Likewise to the other tools of the CBM toolbox, utilizing OBPCA will fetch some resultant benefits that can be shortly listed as:

- A visualized problem cause overview for particular machinery objects
- Better understanding of the relation between existing and potential problems and their causes
- Improvement of lists of common machinery problems and causes in plant’s information system; therefore, possibility of improving the quality and reliability of the input data and output information

On the whole, the CBM toolbox is expected to considerably contribute in running an effective condition based maintenance program with which the potential failures can be foreseen using the most feasible and appropriate nondestructive tests and condition monitoring techniques. Such an outcome is provided taking into account and assessing the factors which influence the applicability of each test or technique plus the essential technical and business parameters from the company’s perspective such as their efficacy, compatibility and safety.

10.4 Suggested Future Work

The future development potentials for the statistical failure analysis, CMT/NDT knowledgebase, the decision support tools and the object based problem and cause analysis are correspondingly expressed in chapters 5, 6, 7 and 8. To highlight, more complicated descriptive and inferential statistics can be used for diagnosis and prognosis of the failure data. The current knowledgebase can be converted into programmable software and the expert knowledge about each CMT/NDT can be further updated and deepen. Moreover, both financial analysis tool and selection matrix can be also integrated into such software. Essentially, other financial factors as well as the concept of interest rates and depreciation can be added to the developed tool. For the OBPCA, the analysis can be carried out for more and more machinery objects; plus, information like operation characteristics and requirements, best predictive, preventive and planned maintenance practices, routine inspection and maintenance procedures for those particular machinery objects can be merged and inserted in a global catalog.

In addition to the above development potentials and as a suggested research work, the concepts of risk based and opportunistic maintenance can also be integrated to the CBM toolbox and its utilization procedure. Risk based maintenance (RBM) has been developed to inspect the high-risk components usually with greater frequency and thoroughness and to maintain in a greater manner, to achieve tolerable risk criteria [27]. Adapting RBM tactic is essential in developing cost effective maintenance programs. The RBM methodology is consisted of four phases: scope identification, risk assessment, risk evaluation, and maintenance planning. Employing this methodology, one is able to estimate risk caused by the unexpected failure as a function of the probability and the consequence of failure [345].

RBM utilizes the probabilistic risk analysis coupled with inspection systems. The RBM system comprises life cycle event trees, unreliability function analysis for field failure database and risk-cost analysis for various maintenance scenarios [182]. Unreliability represents the failure probability as the function of operation hours and number of starts. The basis of unreliability analysis is the statistical database of field failure and damage related to the operation history [22], [311]. Examples of the application of RBM in practice have been shown in the work of Arunraj and Maiti [27], Bareiß et al. [41], and Fujiyama [208]. Having this in mind, for example, the critical objects can be identified not only based on their failure frequency but also by the level of risk associated with their failure. Maintenance of these objects can then be prioritized based on the risk, which helps in reducing the overall risk of the plant.

In opportunistic maintenance, the timing of maintenance actions for equipment and machinery is determined by the procedure for some other object in the same facility or plant. In other words, here a kind of a preventive work that is due and overdue, is done merely when there is an opportunity due to stoppage, breakdown, shutdown, or planned maintenance of other objects [537]. When an equipment or a machine is taken down for maintenance due to a failure, the opportunity can be utilized for maintaining other wearing-out components which still have not been failed. Therefore, it provides the maintenance crew with a prospect to replace or repair those items, which are found to be defective or require replacement in the immediate future, during the maintenance of a subsystem, unit or component [553]. The concept and application of opportunistic maintenance are exclusively discussed in the following references and the references therein: [158], [159], [428].

Formerly, opportunistic maintenance was always implemented under unplanned or reactive maintenance; however, more benefits can be gained when it becomes a preplanned exercise. In the latter case, proper planning can be done with the help of such systems like condition based maintenance. Opportunistic maintenance does have an advantage of carrying out maintenance with no loss of effective operating time. In combination with condition based maintenance, it is really advantageous as the duration of such scheduled stoppage is also not very long [605]. As it can be clearly seen, the concept of opportunistic maintenance can also be fruitfully incorporated in the CBM toolbox. For instance, through statistical failure analysis the age/life time of particular machinery objects can be derived out and in certain cases where a deteriorating object under condition monitoring is to be changed or a process is to be stopped, the opportunity can be used to fix or replace some other objects. All in all, the future research and development (R&D) potentials based on the undertaken doctoral research and the developed CBM toolbox is significant. These R&D potentials are from a very wide range topics related to different aspects of science and business but all can not only advance but revolute the current maintenance practices.

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Appendix A - Material Failure and Defect

It is indispensable to have an overview of different material failure and defects to become familiar with the related technical terminologies and descriptions. Although, it is said that the main root cause of most machinery failures is human fault (i.e. from design to operation), but nevertheless, material failures and defects can be counted as the major intermediate causes of those failures. Operating loads and environmental conditions are often the primary causes leading to a material's failure. If materials were resistant to all failure modes in all environments, a machinery system or component, in theory, could have an infinitely long life. However, because of imperfection of human knowledge or infeasibility of use and application of ideal materials, failures and defects occur [140]. In industry, it is the task of maintenance personnel to know probable failures and defects and seek to prevent the occurrence of those by any means.

a. Corrosion

Corrosion is the electrochemical deterioration of a metal resulting from chemical reaction with the surrounding environment. The most serious consequence of corrosion is a component or system failure. Failure can occur either by sufficient material property degradation, such that the component or structure is rendered unable to perform its intended function, or by fracture that originates from or is propagated by corrosive effects. While corrosion manifests itself in many different forms and through various environments and mechanisms. Corrosion is very common and can be an extremely critical defect. It is associated with considerable amount of expenses which indeed can be eliminated through proper maintenance [348]. Therefore, technicians undertaking any condition monitoring technique or nondestructive test may devote a significant amount of their inspection time to corrosion detection. The following tables contain description and explanation for different types of corrosion [72], [518], [541].

Table A1 Description and explanation of different corrosion types

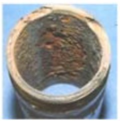
Corrosion Type	Description and Explanation	Image
Dealloying	Dealloying, also called selective leaching, is a less common form of corrosion where one element is targeted and consequently extracted from a metal alloy, leaving behind an altered structure. The most common form of selective leaching is dezincification, where zinc is extracted from brass or other alloys containing zinc. Left behind are structures that have experienced little or no dimensional change, but whose parent material is weakened, porous and brittle.	
Pitting Corrosion	Pitting corrosion, also simply known as pitting, is an extremely localized form of corrosion that occurs when a corrosive medium attacks a metal at specific points causing small holes or pits to form. This usually happens when a protective coating or oxide film is perforated, due to mechanical damage or chemical degradation. Pitting is very dangerous since it is difficult to be anticipated and prevented, relatively difficult to be detected, and occurs very rapidly.	
Crevice Corrosion	Crevice corrosion occurs as a result of water or other liquids getting trapped in localized stagnant areas creating an enclosed corrosive environment. This occurs under fasteners, gaskets, washers and in joints or in other components with small gaps. Crevice corrosion can also occur under debris built-up on surfaces, sometimes referred to as 'poultice corrosion'. Poultice corrosion can be quite severe, due to a gradually increasing acidity in the crevice area.	
Erosion Corrosion	Erosion corrosion is a form of attack resulting from the interaction of an electrolytic solution in motion relative to a metal surface. It has typically been associated with small solid particles dispersed within a liquid stream. The fluid motion causes wear and abrasion, increasing rates of corrosion over uniform one under the same conditions. Erosion corrosion is evident in pipelines, cooling systems, valves, boiler systems, ventilators, propellers and impellers.	
Corrosion Fatigue	Corrosion fatigue is the environmentally-assisted mechanical degradation of a material due to the combined effects of corrosion and fatigue as a direct result of cyclic stress loading. It is often considered to be a subset of stress corrosion cracking, SCC, but their fracture mechanics and methods of prevention are not very similar to each other. SCC occurs under static stress while corrosion fatigue occurs under a cyclic stress, part of which is tensile stress.	
Uniform Corrosion	Uniform corrosion is a generalized corrosive attack that occurs over a large surface area of a material. The result is a thinning of the material until failure occurs. It can also lead to changes in surface properties such as increased surface roughness and friction, which may cause component failure especially in the case of moving parts that require lubricity. In most cases corrosion is inevitable; hence, mitigating its effects is essential to ensuring material longevity.	

Table A2 Description and explanation of different corrosion types

Corrosion Type	Description and Explanation	Image
Hydrogen Damage	Combined factors of hydrogen and residual or tensile stress can damage material. The damage can result in cracking, embitterment, loss of ductility, blistering and flaking. Hydrogen induced cracking refers to the cracking of a ductile alloy under constant stress at presence of hydrogen gas. Hydrogen embrittlement is the brittle fracture of a ductile alloy during plastic deformation in the same milieu. It is seen in low strength alloys, also in steels, and aluminum and nickel alloys.	
Galvanic Corrosion	Galvanic corrosion is a form of corrosive attack that occurs when two dissimilar metals (e.g. stainless steel and magnesium) are electrically connected, either through physically touching each other or through an electrically conducting medium, such as an electrolyte. When this occurs, an electrochemical cell can be established, resulting in an increased rate of oxidation of the more anodic material (i.e. lower electrical potential).	
Intergranular Corrosion	Intergranular corrosion attacks the interior of metals along grain boundaries. It is associated with impurities, which tend to deposit at grain boundaries, and/or a difference in crystallographic phase precipitated at grain boundaries. Heating of some metals can cause a 'sensitization' or an increase in the level of inhomogeniety at grain boundaries. Therefore, some heat treatments and weldments can result in a propensity for Intergranular corrosion.	
Stress Corrosion Cracking	Stress corrosion cracking, SCC, is an environmentally induced cracking phenomenon that sometimes occurs when susceptible metals are subjected to a tensile stress and a corrosive environment simultaneously. Moreover, SCC is not defined as the cause of cracking that occurs when the surface of the metal is corroded resulting in the creation of a nucleating point for a crack. Rather, it is a synergistic effort of a corrosive agent and a modest, static stress.	

b. Fatigue

Fatigue is a very frequent failure mode and deserves substantial consideration since it can impose damage on a material at a stress level that is quite less than the material's design limit. Fatigue has been attributed with playing a role in nearly 90% of all material structural failures. A component that fractures into two or more pieces after being subjected to a cyclic stress or fluctuating load over a period of time is considered to have failed by fatigue. The maximum value of the cyclic stress for fatigue failure is less than the material's ultimate tensile strength. It is often the case that the maximum value of the cyclic stress is so low that if it were applied at a constant level the material would be able to easily support the load without incurring any damage [285].

As Craig explains, the fatigue failure mechanism involves three phases: crack initiation, crack propagation, and material rupture. Fatigue cracks are often initiated by material inhomogeneities, such as notches, grooves, surface discontinuities, flaws, and other material defects [140]. These inhomogeneities or initiation points act as stress raisers where the applied stress concentrates until it exceeds the local strength of the material and produces a crack. In fact, fatigue is a stochastic process, often showing considerable scatter even in controlled environments. Fatigue life is influenced by a variety of factors such as temperature, surface finish, presence of oxidizing or inert chemicals, residual stresses, and fretting.

Cyclic loads cause the initiation and growth of a crack, and ultimately, when the crack has weakened the material to a point such that it can no longer support the applied load it will rupture, which can occur by shear or by tension. Fatigue is not so much dependent on time as it is the number of cycles. A cycle consists of an applied stress being increased from a starting value up to a maximum value and then decreasing past the starting point down to a minimum value, and finally back up to the starting value. Metals and polymers are typically susceptible to fatigue failure, while ceramics tend to be resistant. There exist different types fatigue and these are briefly described in table A3, in the next page [140].

Here are two important points to be explained. First is that at high temperatures creep and fatigue can act simultaneously to produce an intensive and damaging effect on materials. A material operating in high temperature conditions can experience both creep strains and cyclic strains that can seriously compromise the material's expected lifetime. To illustrate, if a material experiences creep strains while undergoing fatigue cycling, its fatigue life can be greatly reduced. Similarly, if a material experiences fatigue cycling while undergoing creep, its creep life can be significantly reduced.

Second is a failure mode which called as spalling: deterioration of a component as fragments from the surface break free from the material. This phenomenon can occur through several mechanisms including the formation and propagation of fatigue cracks underneath the surface. This mechanism is related to the surface fatigue mechanism. Another mechanism that leads to spalling is thermal shock, which is a failure mechanism that occurs in materials that exhibit a significant temperature gradient (i.e. rate of change temperature with distance in any given direction around a particular location) can cause spalling failure. Spalling can occur in metals or ceramics or even surface coatings; it often occurs in armor materials, gear teeth, and bearings.

Table A3 Description and explanation of different fatigue types

Fatigue Type	Description and Explanation
Impact Fatigue	Impact fatigue occurs when a material is subjected to repeated impacts to a localized area causing the initiation and propagation of a fatigue crack. This repeated impact loading can ultimately result in fatigue fracture.
Surface Fatigue	Surface or contact fatigue occurs when two material surfaces that are in contact with each other in a rolling or combined rolling and sliding motion that generate an alternating force or stress oriented in a direction normal to the surface. The contact stress initiates the formation of cracks slightly beneath the surface, which then grow back toward the surface causing pits to form, as particles of the material are ejected or worn away. This form of fatigue is common in applications where an object repeatedly rolls across the surface of a material resulting in a high concentration of stress at each point along the surface.
Fretting Fatigue	Fretting damage on the surface of a material can act as a nucleating point for a crack. Under cyclic loading (typically small amplitude loading) the nucleation of a crack at the location of fretting damage and the subsequent crack propagation and fracture of the material constitutes fretting fatigue. Fretting of a component under fatigue conditions will lead to a much quicker nucleation of cracks than fatigue of a component not subjected to fretting. Furthermore, cracks can be initiated by fretting damage at a much lower stress than if the material is in a normal, undamaged condition.
Thermal Fatigue	Simple temperature fluctuations or repeated heating and cooling can impose stresses on a material leading to fatigue damage and potentially failure. Materials generally exhibit a dimensional change or strain to some extent in response to temperature changes. This response can be significant in some materials, especially metals, and can induce thermal stresses on the material if it is mechanically confined in some way. When a material is exposed to conditions of fluctuating temperatures it can cause cyclic fatigue loading, which can result in crack growth and possibly fracture. This process is referred to as thermal fatigue.
Low-cycle Fatigue	A fatigue failure that occurs after a relatively small number of cycles is considered to be low-cycle fatigue. Typically, when a material fails due to fatigue after less than 10,000 cycles, it is considered to be low-cycle fatigue. The mechanisms of crack growth for materials experiencing low-cycle fatigue are similar to the crack growth of a material subjected to a constant stress. The deformation exhibited by a material subjected to low-cycle fatigue is typically plastic.
High-cycle Fatigue	High-cycle fatigue is defined as fatigue where the material is subjected to a relatively large number of cycles before failure occurs. Generally, for the fatigue mechanism to be considered high-cycle fatigue the number of cycles required to produce failure is greater than 10,000. The deformation exhibited by a material subjected to high-cycle fatigue is typically elastic.

c. Fracture

Fracture is defined as the local separation of a material into two or more pieces under the action of stress. The central difficulty in designing against fracture in high-strength materials is that the presence of cracks can modify the local stresses to such an extent that the elastic stress analyses done so carefully by the designers are insufficient. When a crack reaches a certain critical length, it can propagate catastrophically through the structure, even though the gross stress is much less than would normally cause yield or failure in a tensile specimen. The term ‘fracture mechanics’ refers to a vital specialization within solid mechanics in which the presence of a crack is assumed, and we wish to find quantitative relations between the crack length, the material’s inherent resistance to crack growth, and the stress at which the crack propagates at high speed to cause structural failure [267]. Fracture mechanics is a destructive method for predicting failure of a structure containing a crack by pulling apart two sides of the crack and acquiring information about the specimen’s integrity. Nevertheless, there exist NDTs such as acoustic emission testing to predict fracture occurrence in a nonintrusive way [530]. Fracture is classified into different types which are tabulated and briefly explained in the next page based on the information retrieved from different scientific sources [140], [267].

Table A4 Description and explanation of different fracture types

Fracture Type	Description and Explanation
Creep	Creep is a time-dependent process where a material under an applied stress undergoes a dimensional change. The process is also temperature-dependent since the creep or dimensional change that occurs under an applied stress increases considerably as temperature increases. A material experiences creep failure when the dimensional change renders the material useless in performing its intended function. Sufficient strain or creep can result in fracture, known as stress rupture, which is discussed briefly in a subsequent section. Creep occurs when vacancies in the material's microstructure migrate toward grain boundaries that are oriented normal to the direction of the applied stress.
Yielding	Yielding failure (also known as gross plastic deformation) occurs when a material subject to mechanical loading exhibits sufficient plastic deformation such that it can no longer perform its intended function. This mode of failure results in deflected, stretched, or otherwise misshapen components, and is typical in ductile materials such as metals and polymers. Ceramics and very hard metals are inherently brittle materials and therefore yielding is not a significant concern.
Buckling	Buckling occurs when a material subjected to compressive or torsional stresses can no longer support the load, and it consequently fails by bulging, bending, bowing or forming a kink or other unnatural characteristic. Bars, tubes, and columns are shapes that are commonly susceptible to failure by buckling. In addition, I-beams and other more complex geometries may experience buckling under compressive or torsional loads. Buckling is dependent on the shape and respective dimensions of the material as well as the modulus of elasticity, which is dependent on temperature. Therefore, buckling is more likely to occur at higher temperatures where the modulus of elasticity is lower, since materials have a tendency to soften when they are heated.
Brittle Fracture	Brittle fracture occurs when mechanical loads exceed a material's ultimate tensile strength causing it to fracture into two or more parts without undergoing any significant plastic deformation or strain failure. Material characteristics and defects such as notches, voids, inclusions, cracks, and residual stresses are the typical initiation points for the formation of a crack leading to brittle fracture. Once the crack is initiated the material will undergo catastrophic failure fairly quickly under a sustained load. This failure mode commonly occurs in brittle materials such as ceramics and hard metals.
Stress Rupture	Stress rupture, also known as creep fracture, is a mechanism that is closely related to creep except that the material eventually fractures under the applied load. Creep is the time- and temperature-dependent elongation of a material that is subjected to a stress. When this stress overcomes the material's ability to strain, it will rupture. Cracking that precedes the rupture of the material can be either transgranular or intergranular. Transgranular indicates that a crack proceeds through grain boundaries and across the grain, whereas, intergranular indicates that a crack navigates around or between grain boundaries.
Creep Buckling	Creep buckling is a failure mode that occurs when the creep process renders a material unable to support loads it could otherwise handle, and as a result the material buckles.
Ductile Fracture	Ductile fracture occurs when a material experiences substantial plastic deformation or strain while being stressed beyond its yield strength and is consequently torn in two pieces. An extensive amount of energy is absorbed during the deformation process. Similar to brittle fracture, cracks are typically nucleated at material defects, such as voids and inclusions. As ductile materials experience plastic deformation, existing voids coalesce to form the crack tip. The actual crack propagation process in ductile fracture is generally a slow process with the crack growing at a very moderate rate as voids coalesce at the fracture surface. An obvious but important consideration is that this type of failure is common in ductile materials, typically metals and polymers.
Elastic Distortion	A material can fail without being permanently changed when it is elastically deformed to such an extent that it fails to perform its intended function. Elastic deformation occurs when a material is subjected to a load that does not exceed its yield strength. Elastic distortion can be induced by a load and affected by a change in temperature. For example, a material's elastic modulus is temperature dependent, and if an unanticipated temperature change occurs the material may undergo elastic deformation at a smaller load than it would at the normal operating temperature.
Thermal Relaxation	Thermal relaxation is a process related to the temperature dependent creep failure mode. Failure by thermal relaxation commonly occurs in fastener materials or other materials that are prestressed such that they could support a greater load than their non-prestressed counterpart. As the material undergoes creep at high temperatures their residual stresses are relieved which may render the material unable to support the given load.

d. Wear

Bhushan defines wear as the surface damage or removal of material from one or both of two solid surfaces in a sliding, rolling, or impact motion relative to one another [70]. Wear usually occurs through surface interactions at asperities. During relative motion, first, material on the contacting surface may be displaced so that the properties of the solid body, at least at the surface, are altered, but little or no material is actually lost.

Later, material may be removed from a surface and may result in the transfer to the mating surface or may break loose as a wear particle. In the case of transfer from one surface to another, net volume or mass loss of the interface is zero, although one of the surfaces is worn. Definition of wear is generally based on loss of material, but it should be underlined that due to material displacement on a given body, with no net change in weight or volume, also constitutes wear.

Wear is not material property; it is a system reaction and operating conditions affect interface wear. Mistakenly, it is sometimes assumed that high-friction interfaces exhibit high wear rates. This is not necessarily true. For instance, interfaces with solid lubricants and polymers exhibit relatively low friction and relatively high wear, whereas ceramics exhibit moderate friction but extremely low wear. Wear occurs by mechanical and/or chemical means and is generally accelerated by frictional heating or thermal means. Wear can be classified into seven different categories as adhesive wear, abrasive wear, fatigue wear, impact wear (erosion and percussion), chemical or corrosive wear, electrical-arc-induced wear, and fretting wear.

1. ***Adhesive wear*** occurs when two nominally flat solid bodies are in sliding contact, whether lubricated or not. Adhesion or bonding occurs at the asperity contacts at the interface and these contacts are sheared by sliding, which may result in detachment of a fragment from one surface and attachment to the other surface. As the sliding continues, the transferred fragments may come off the surface on which they are transferred and be transferred back to the original surface, or else form loose wear particles. Some are fractured by a fatigue process during repeated loading and unloading action resulting in formation of loose particles [71], [318].

2. ***Abrasive wear*** occurs when asperities of a rough, hard surface or hard particles slide on a softer surface and damage the interface by plastic deformation or fracture. In the case of ductile materials with high fracture roughness like metals and alloys, hard asperities or hard particles result in the plastic flow of the softer material. Most metallic and ceramic surfaces during sliding show clear evidence of plastic flow, even some for ceramic brittle materials [71], [498].

3. ***Fatigue wear***, also known as surface fatigue, is observed at materials' subsurface and surface during repeated rolling (negligible friction) and sliding respectively. The repeated loading and unloading cycles to which the materials are exposed may include the formation of subsurface or surface cracks which eventually after a critical number of cycles, will result in the breakup of the surface with the formation of large fragments, leaving large pits on the surface, also known as pitting. Prior to this critical point negligible wear takes place that is in absolute contrast to the wear by an adhesive or abrasive mechanism, where wear cause a gradual deterioration from the start of running [363], [594], [658]

4. ***Impact wear*** includes two broad types of wear phenomena erosive and percussive wear. Erosion can occur by jets and streams of solid particles, liquid droplets and implosion of bubbles formed in the fluid. As in case of Abrasive wear, erosive wear happens by plastic deformation and/or brittle fracture [76], [258], [288]. Cavitation, a form of erosion, is defined as the repeated nucleation, growth and violent collapse of cavities or bubbles in a liquid, hence, cavitation erosion arises when a solid and fluid are in relative motion and bubbles formed in the fluid become unstable and implode against the surface of the solid [252], [490]. Percussion occurs from repetitive solid body impacts. These repeated impacts result in progressive loss of solid material [180].

5. ***Chemical or corrosive wear*** occurs when sliding takes place in a corrosive environment. In air the most dominant corrosive medium is oxygen. Therefore chemical wear in air is generally called oxidative wear. It is essential to note that chemical wear requires both chemical reaction (corrosion) and rubbing and occurs in a highly corrosive environment plus in high-temperature and high-humidity environments [70]. As another form, electrochemical corrosion is a chemical reaction accompanied by the passage of the electrical current, and for this to occur, a potential difference must exist between two regions. Electrochemical wear may accelerate in a corrosive environment because corrosive fluids may provide the necessary conductive medium on rubbing surfaces [595]. Besides, friction modifies the kinetics of chemical reactions of sliding bodies, and with gaseous or liquid environment, to the extent that reactions that occur at high temperatures occur at moderate ones; wear which is controlled by this fact is usually referred to as tribochemical wear [195], [260].

6. *Electrical-arc-induced wear* is a specific type of wear which is occurred as following: when a high potential is present over a thin air layer in a sliding process, a dielectric breakdown results that leads to arcing. During arcing, a relatively high-power density occurs over a very short period of time. The generated heating results in considerable melting and subsequent re-solidification, corrosion, hardness changes and even in direct ablation of material [237]. Arcing can thus initiate several modes of wear, resulting in catastrophic failures in electrical machinery. To prevent such wear one can eliminate the gap between two surface with potential difference, provide and insulator of adequate dielectric strength between the two surfaces, provide a low impedance connection between the two surfaces to eliminate the potential difference and to have one of the surface not ground. For instance, bearings should be press-fitted to the shaft and conducting grease should be used to abolish possible arcing [69].

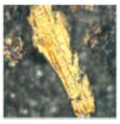
7. *Fretting wear* occurs when surfaces, which are in intimate contact with each other, are subject to a small amplitude relative motion that is cyclic in nature, such as vibration. Fretting wear is normally accompanied by the corrosion or oxidization of the debris and worn surface. Unlike normal wear mechanisms only a small amount of the debris is lost from the system; instead the debris remains within the conjoined surfaces. The mated surfaces essentially exhibit adhesion through mechanical bonding, and the oscillatory motion causes the surface to fragment, thereby creating oxidized debris. If the debris becomes embedded in the surface of the softer metal, the wear rate may be reduced. If the debris remains free at the interface between the two materials the wear rate may be increased. Fatigue cracks also have a tendency to form in the region of wear, resulting in a further degradation of the material's surface [353].

Wear, by all mechanisms except by fatigue, occurs by gradual removal of material. Of the abovementioned wear mechanisms, one or more may be operating in one particular machine or equipment. In many cases, wear is initiated by one mechanism and it may proceed by other mechanisms, thus complicating failure analysis. Besides, contamination, process in which a medium becomes unclean or impure by other substance, is a common phenomenon for most lubricated mechanical systems and is the most common cause of premature equipment failure. Contamination will cause degradation of the lubricant and acceleration of the wear rate of machinery. Contamination can occur either externally or internally. External contamination can come from sand, dirt, fibers and other environmental debris and is typically the result of failed seal systems and/or failed filters. These types of contaminants can sometimes be detected as elevated levels of silicon, sodium, aluminum or boron in liquids (e.g. machinery oil and lubricants). On the other hand, internal contamination is typically caused by lubricant degradation and wear debris [132].

As Raadnui declares, lubricant degradation is indeed a result of different factors such as life-time of the oil or lubricant, elevation of temperature in the medium, presence (i.e. leakage from other components) of air, water and fuel in machinery systems [497]. However, wear debris is considered to be the most important type of internal contaminants, not only for the negative effect they have on oil and lubricant quality but also for the precious information they carry about machinery condition. The essential requirement in terms of wear is to determine its extent and rate of change in relation to the type of wear and its source. Debris particles generated by different wear mechanisms have characteristics, which can be identified with the specific wear mechanism [356], [581].

Debris particles can be classified based on wear mechanism or their morphology. Particles collected from a wear test may not be in the same state in which these were first produce because of changes in subsequent sliding or circulation. It is usually difficult to identify the exact possible wear mechanism; hence, particles are generally classified based on their morphology. However, in more recent technical literature there exist blended classifications that are focused both on morphology and wear mechanism. Yet, contaminant particles are generally considered the single most significant cause of abnormal component wear. The wear initiated by contaminants generally induces the formation of larger particles, with the formation rate being dependent on the filtration efficiency of the system. In fact, once a particle is generated and moves with the lubricant, it is technically a contaminant. A brief review of different wear particle types, and related descriptions and explanations, is tabulated in the page based on the information retrieved from various scientific and technical sources [24], [70], [151], [165], [279], [273], [355], [543], [515], [589].

Table A5 Description and explanation of different wear particle types

Wear Particle Type	Description and Explanation	Image
Normal-Rubbing Wear Particles	Normal-rubbing wear particles are generated as the result of normal wear in a machine and result from exfoliation of parts of the shear mixed layer. Rubbing wear particles consist of flat platelets, generally 5 microns or smaller, although they may range up to 15 microns depending on equipment application. There should be little or no visible texturing of the surface and thickness should be one micron or less.	
Severe Sliding Wear Particles	Severe sliding wear particles are identified by parallel striations on their surfaces. These striations are parallel to each other and the long axis of the particle. They are generally larger than 15 microns, with the length-to-width thickness ratio falling between 5 and 30 microns. Severe sliding wear particles sometimes show evidence of temper colors, which may change the appearance of the particle after heat treatment.	
Bearing Wear Particles	These distinct particle types have been associated with rolling bearing fatigue. Fatigue spall particles constitute actual removal from the metal surface when a pit or a crack is propagated. These particles reach a maximum size of 100 microns during the micro spalling process. Fatigue spalls are generally flat with a major dimensions-to-thickness ratio of 10 to 1. They have a smooth surface and a random, irregularly shape circumference. Laminar Particles are very thin free metal particles with frequent occurrence of holes. They range between 20 and 50 microns in major dimension with a thickness ratio of 30:1. These particles are formed by the passage of a wear particle through a rolling contact. These may be generated throughout the life of a bearing, but at the onset of fatigue spalling, the quantity generated increases. An increasing quantity of laminar particles is indicative of either spherical wear or rolling-bearing fatigue micro-cracks.	
Cutting Wear Particles	Cutting wear particles are generated as a result of one surface penetrating another. There are two ways of generating this effect. A relatively hard component can become misaligned or fractured, resulting in hard sharp edge penetrating a softer surface. Particles generated this way are generally coarse and large, averaging 2 to 5 microns wide and 25 microns to 100 microns long. Hard abrasive particles in the lubrication system, either as contaminants such as sand or wear debris from another part of the system, may become embedded in a soft-wear surface such as a lead/tin alloy bearing. The abrasive particles protrude from the soft surface and penetrate the opposing wear surface. The maximum size of cutting wear particles generated in this way is proportional to the size of the abrasive particles in the lubricant. The presence and quantity of cutting wear particles should be carefully monitored. If the majority of cutting wear particles in a system is around a few micrometers long and a fraction of a micrometer wide, the presence of particulate contaminants should be suspected. If a system shows increased quantities of large (i.e. around 50 micrometers long) cutting wear particles, a component failure is potentially imminent. This can be used as a preventive measure in maintenance.	
Gear Wear Particles	Two types of wear have been associated with gear wear. One is pitch line fatigue particles from a gear pitch line that have much in common with rolling-element bearing fatigue particles. They generally have a smooth surface and are frequently irregularly shaped. Depending on the gear design, the particles usually have a major dimension-to-thickness ratio between 4:1 and 10:1. The chunkier particle result from tensile stresses on the gear surface causing the fatigue cracks to propagate deeper into the gear tooth. Second are scuffing or scoring particles is caused by too high a load and/or speed. The particles tend to have a rough surface and jagged circumference. Even small particles may be discerned from rubbing wear by these characteristics. Some of the large particles have striations on their surface indicating a sliding contact. Because of the thermal nature of scuffing, quantities of oxide are usually present and some of the particles may show evidence of partial oxidation, that is, tan or blue temper colors.	
Spherical Particles	These particles are generated in the bearing fatigue cracks. If generated, their presence provides an early warning of impending trouble as they are detectable before any actual spalling occurs. Rolling bearing fatigue is not the only source of spherical metallic particles. They are known to be generated by welding or grinding processes. Spheres produced in fatigue cracks may be differentiated from those produced by other mechanisms through their size. Rolling fatigue generates few spheres over 5 microns in diameter while the spheres generated by welding and grinding are frequently over 10 microns in diameter.	

Example Images of Wear Particles

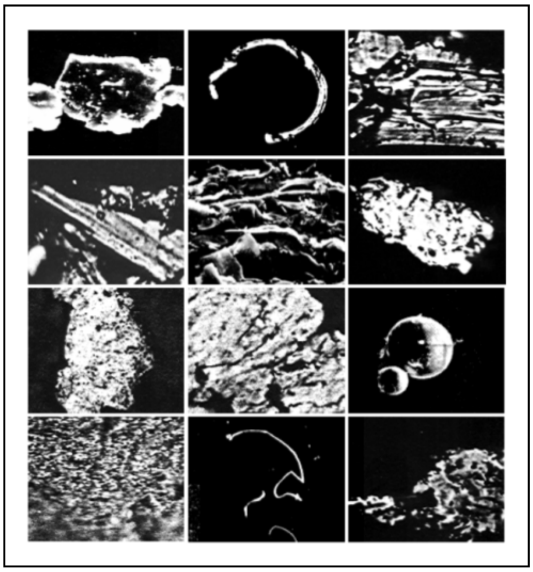


Figure A1 Different wear particles with variety of shapes and structures [356]

e. Flaw

It is essential to know where flaws occur or can be expected to exist and what effect they can have in each of the NDT methods. Misinterpretation and/or improper evaluation of flaws or improper performance of CMT/NDT can result in misevaluation of the parts under inspection or service. There are different types of flaws which can be named as: in-service flaws, inherent flaws, primary processing flaws, and secondary processing or finishing flaws.

1. *In-service flaws* are formed after all fabrication has been completed and the machinery object or related component has gone into service. These flaws are attributable to aging effects caused by either time, cycles of use, service operating conditions, or combinations of these effects. The following are brief descriptions of some in-service flaws.

Table A6 Description and explanation of different in-service flaws

In-Service Flaw Type	Description and Explanation
Delamination	Delamination is a technical term used to define the separation of composite material layers within a monolithic structure. Ultrasonic is the primary non-destructive test employed for the detection of delamination in composite structures.
Fatigue Crack	Fatigue cracks occur in parts that have been subjected to repeated or changing loads while they are in service, such as riveted lap joints in different machinery. The crack usually starts at a highly-stressed area and propagates through the section until failure occurs. A fatigue crack will start more readily where the design or surface condition provides a point of stress concentration. Common stress concentration points are: fillets, components with sharp radii, and structures with poor surface finish, seams or grinding cracks.
Overstress Crack	Overstress cracks occur when a part is stressed beyond the level for which it was designed. Such overstressing can occur as the result of an impact and collide or related damage due to some unusual or emergency conditions not anticipated by the designer, or because of the failure of some related structural member.
Unbond or Disbond	Unbond or disbond is a flaw where adhesive attaches to only one surface in an adhesive-bonded assembly. It can be the result of crushed, broken, or corroded cores in adhesive- bonded structures. Areas of unbonds have no strength and place additional stress on the surrounding areas making failure more likely.
Stress Corrosion Crack	Stress corrosion cracks develop on the surface of the parts that are under tension stress in service and are also exposed to a corrosive environment, such as sump areas and areas between two metal parts of faying surfaces.

2. *Inherent flaws* are present in metal as the result of its initial solidification from the molten state, before any of the operations to forge or roll it into useful sizes and shapes have begun. There exist different kinds of inherent flaws which are briefly expressed in table A7, in the next page.

Table A7 Description and explanation of different inherent flaws

Inherent Flaw Type	Description and Explanation
Porosity	Porosity is holes on a material surface or scattered throughout the material, caused by gases being liberated and trapped as the material solidifies.
Inclusion	Inclusions are impurities such as slag, oxides and sulfides, which occur in ingots and castings. Inclusions are commonly caused by incomplete refining of the metal ore (i.e. mineral from which metal can be extracted) or the incomplete mixing of deoxidizing materials added to the molten metal in the furnace.
Blowhole	Blowholes are secondary pipe holes in metal that can occur when gas bubbles are trapped as the molten metal in an ingot mold solidifies. Many of these blowholes are clean on the interior and are welded shut into sound metal during the first rolling or forging of the ingot. However, some do not weld and can appear as seams or laminations in finished products.
Segregation	Segregation is a non-uniform distribution of various chemical constituents that can occur in a metal when an ingot or casting solidifies. Segregation can occur anywhere in the metal and is normally irregular in shape. However, there is a tendency for some constituents in the metal to concentrate in the liquid that solidifies last.
Primary Pipe	Primary pipe is a shrinkage cavity that forms at the top of an ingot during metal solidification, which can extend deep into the ingot. Failure to cut away all of the ingot shrinkage cavity can result in unsound metal, called pipe, that shows up as irregular voids in finished products.
Shrinkage Crack	Shrinkage cracks occur in castings due to stresses caused by the metal contracting as it cools and solidifies. The shrinkage crack can be controlled by maintaining the mold temperature at the crack point by reducing the cycle time, improving the spray pattern, adding gates, using oil lines for heating purpose.

3. *Primary processing flaws* occur while working the metal down by hot or cold deformation into useful shapes such as bars, rods, wires, and forged shapes are primary processing flaws. Casting and welding are also considered primary processes although they involve molten metal, since they result in a semi-finished product. Tables A8 and A9 name some primary processing flaws and they include brief descriptions of these flaws.

Table A8 Description and explanation of different primary processing flaws

Primary Processing Flaw Type	Description and Explanation
Scale	Scale is an oxide formed on metal by the chemical action of the surface metal with oxygen from the air.
Flake	Flakes are internal ruptures that can occur in metal as a result of cooling too rapidly. Flaking generally occurs deep in a heavy section of metal. Certain alloys are more susceptible to flaking than others.
Seam	Seams are surface flaws, generally long, straight, and parallel to the longitudinal axis of the material, which can originate from ingot blowholes and cracks, or be introduced by drawing or rolling processes.
Hot Tear	Hot tear is a pulling apart of the metal that can occur in castings when the metal contracts during solidification.
Cupping	Cupping is a series of internal metal ruptures created when the interior metal does not flow as rapidly as the surface metal during drawing or extruding processes. Segregation in the center of a bar usually contributes to the occurrence.
Cold Shut	Cold shut is a failure of metal to fuse. It can occur in castings when part of the metal being poured into the mold cools and does not fuse with the rest of the metal into a solid piece.
Lamination	Laminations are flaws formed in rolled plate, sheet, or strip when blowholes or internal fissures are not welded tight during the rolling process and are enlarged and flattened into areas of horizontal discontinuities.
Forging Lap	Forging laps are flaws as results of metal being folded over and forced into the surface, but not welded to form a single piece. They can be caused by faulty dies, oversized dies, oversized blanks, or improper handling of the metal in the die. They can occur on any area of the forging.
Forging Burst	Forging bursts are internal or external ruptures that occur when forging operations are started before the material to be forged reaches the proper temperature throughout. Hotter sections of the forging blank tend to flow around the colder sections causing internal bursts or cracks on the surface. Too rapid or too severe a reduction in a section can also cause forging bursts or cracks.

Table A9 Description and explanation of different primary processing flaws

Primary Processing Flaw Type	Description and Explanation
Cooling crack	Cooling cracks occur in casting due to stresses resulting from cooling, and are often associated with changes in cross sections of the part. Cooling cracks can also occur when alloy and tool steel bars are rolled and subsequently cooled. Such cracks are generally longitudinal, but not necessarily straight. They can be quite long, and usually vary in depth along their length.
Slag Inclusion	Slag inclusion is basically a nonmetallic solid material that becomes trapped in the weld metal or between the weld metal and the base metal.
Weld Crater Crack	Weld crater cracks are star shaped cracks that can occur at the end of a weld run.
Weld Undercutting	Weld undercutting is a decrease in the thickness of the parent material at the toe of the weld caused by welding at too high a temperature.
Crack in Weld Metal	Cracks in weld metal are flaws caused by the contraction of a thin section of the metal cooling faster than a heavier section or by incorrect heat or type of filler rod. They are one of the more common types of flaws found in welds.
Incomplete Weld Fusion	Incomplete wells fusion occurs in welds where the temperature has not been high enough to melt the parent metal adjacent to the weld.
Incomplete Weld Penetration	Incomplete weld penetration is a failure of the weld metal to penetrate completely through a joint before solidifying.
Crack in Weld Heat-affected Zone	Cracks in weld heat-affected zone occur because of stress induced in the material adjacent to the weld by its expansion and contraction from thermal changes.

4. *Secondary Processing or Finishing Flaws* are those flaws associated with the various finishing operations, after the part has been rough-formed by rolling, forging, casting or welding. Flaws may be introduced by heat treating, grinding, and similar processes. The followings are brief descriptions of some secondary processing or finishing flaws.

Table A10 Description and explanation of different secondary processing flaws

Secondary Processing Flaw Type	Description and Explanation
Plating Crack	Plating cracks occur when hardened surfaces are electroplated. Generally, they are found in areas where high residual stresses remain from some previous operation involving the part.
Etching Crack	Etching cracks occur when hardened surfaces containing internal residual stresses are etched in acid or acidic liquids.
Grinding Crack	Grinding cracks are thermal one similar to heat treating cracks and can occur when hardened surfaces are ground. The overheating created by the grinding can be caused by the wheel becoming glazed so that it rubs instead of cutting the surface, by using too little coolant, by making too heavy a cut or by feeding the material too rapidly. Generally, the cracks are at right angles to the direction of grinding and in severe cases a complete network of cracks can appear. Grinding cracks are usually shallow and very sharp at their roots; this makes them potential sources of fatigue failure.
Machining Tear	Machining tear is flaws occur when working a part with a dull cutting tool or by cutting to a depth that is too great for the material being worked. The metal does not break away clean, and the tool leaves a rough, torn surface which contains numerous short discontinuities that can be classified as cracks.
Heat treating Crack	Heat treating cracks are caused by stresses formed through unequal heating or cooling of portions of a part during heat treating operations. Generally, they occur where a part has a sudden change of section that could cause an uneven cooling rate, or at fillets and notches that act as stress concentration points.

Appendix B - Fault Detection, Diagnostics and Prognostics

Fault is described as something that detracts from the integrity, functioning, or perfection of something else. In this sense, management of fault is of great concern. Fault management deals with detection, diagnosis and prognosis of faults. Properly implemented fault management can keep a plant running at an optimum level, minimizing of downtime and providing a measure of fault tolerance, which is the ability of a system to respond gracefully to an unexpected failure. In fault management, a set of functions or applications designed specifically for detection, diagnostics and prognostics. Some important functions include: definition of thresholds for potential failure conditions, constant monitoring of system status, continuous scanning for failure threats, diagnostics, controlling of system elements, tracing the locations of potential and actual faults and malfunctions, correction of potential problem-causing conditions, resolution of actual failures and recording of all data in details [271], [297], [365].

a. Fault Detection

Conventionally, the difference between fault detection and fault diagnosis is not clear. However, they can be divided into separate tasks to highlight the differences. Fault detection can be defined as deviation of a measurement parameter from a range that representing normal operation. Such deviation indicates existence of a faulty condition. Given that, measurement parameters are recorded, what is needed for fault detection is a definition of an acceptable range for the measurement parameters to fall within. There are two methods for setting suitable ranges: comparison of recorded measures to known standards, and comparison of the recorded measures to acceptance limits [562].

b. Fault Diagnostics

Diagnosis means the identifying of the nature or cause of something, especially a problem or fault. In a similar way, diagnostic is defined as a test, procedure, or instrument used to identify the nature or cause of a disorder or problem. In technical texts one can find alike definitions, for example, Lewis and Edwards define diagnosis as “fault recognition and identification”, i.e. a means to find out where something will go wrong and possibly even why [371]. Fault diagnosis aims to identify the problem and determine the required corrective actions. It is an information intensive phase, where maintenance crew traditionally relies on technical publications for information covering fault diagnosis procedures, configuration details, and functionality descriptions [335], [678].

Depending on the type of equipment being monitored and the maintenance strategy being followed, once a faulty condition has been detected and the severity of the fault assessed, repair work or replacement will be scheduled. This information then allows for a more accurate estimation of the remaining life, the replacement parts that are needed, and the maintenance tools, personnel, and time required to repair the machinery. For these reasons, and many more, it is often advantageous to have some idea of the fault type that exists before decisions regarding maintenance actions are made. There are obviously a large number of different potential fault types [371]. The description of these faults can be systemized somewhat by considering the type of defect characteristics. In this way, a diagnostic pattern can be developed for the different types of faults that are common in a given facility or plant. Further reading on machinery diagnostics can be found in references [176], [224], [507], and [669]. Condition based fault diagnosis can be divided into the following three categories:

1. *Rule Based Diagnostics:* This diagnostic method, abbreviated as RBD, consists of a knowledgebase and a set of rules the system use to diagnose or predict a fault. These rules may be derived from experts in their field, and are then compiled into a set of rules. Extracting, validating, and verifying the rule base is indispensable in such systems because one faulty rule may demolish the entire result and make the system unreliable. This is often referred to as the ‘brittleness’ of rule based systems. The expert turn out to be the so called ‘knowledge acquisition bottleneck’ and RBD is updated and enlarged once conditions change or new knowledge id developed. A set of rules in a rule based diagnostic system may be translated to a decision tree traversed to determine the fault. This can only be possible if the rules meet a number of criteria (e.g. being deterministic). In some applications, the rules may be induced automatically in the system. Moreover, if statistics and fuzzy logic are used, these systems become powerful diagnostic tools for industry [671].

2. *Case Based Diagnostics:* This diagnostic method, known as RBD, is centered on case based reasoning (CBR), a method from artificial intelligence, based in a cognitive model of learning from experience. Cases capture both a specific situation or problem, and its solution. When a new problem occurs, it is compared with the case library and similar cases are retrieved. These cases are adapted, using domain knowledge, to fit the current problem. The solution in the case is reused after validation or verification and if essential, revised. The problem and the new solution are added to the case library as a new case. RBD is used in situations where the task to create a large and consistent rule base is too difficult or where model based diagnosis is improper. If statistics and feedback (automatic, semi-automatic or manual) is included in the cases, the system will not only improve performance with the addition of new cases, but also with experience derived from feedback [671].

3. *Model Based Diagnostics:* This method is a powerful solution if a complete model of the equipment to monitor can be created. The model is used to detect any deviations and if a deviation is detected the model is used to recognize the problem. The abstraction level of the model is the limiting factor for what faults are detectable. If it is possible to build a model based diagnostic systems, this is the most desirable diagnostic system. This is a manual process to build a model and unfortunately it is difficult to build a model detailed enough for a majority of industrial applications where diagnostic systems are desirable. If a model can be built, real-time simulation is to computationally costly or impossible with available computers [671].

c. Fault Prognostics

Prognosis or prognostic is a prediction about how a situation will develop. Lewis and Edwards define it as “prediction of when a failure may occur”, i.e. a tool to compute remaining useful life of an asset [371]. To be able to provide reliable prognostic, reliable diagnostic must be already available. Some of the recent diagnostic systems are able to make predictions of a fault’s occurrence time and its probability. This information may be used as input by a prognostic system to predict a future health profile and estimate remaining useful life of some asset, given a required reliability level and safety limit. Afterwards, this information may be used to generate a prognosis of the overall reliability of a large system. The weakest parts of a system can be then identified and counter measurements can be taken to stay within some specified reliability and safety limits. In maintenance framework, these measurements may be different maintenance tasks or measurements to ensure certain spare parts are available or redundant production capacity is within access within a certain time period [60], [614].

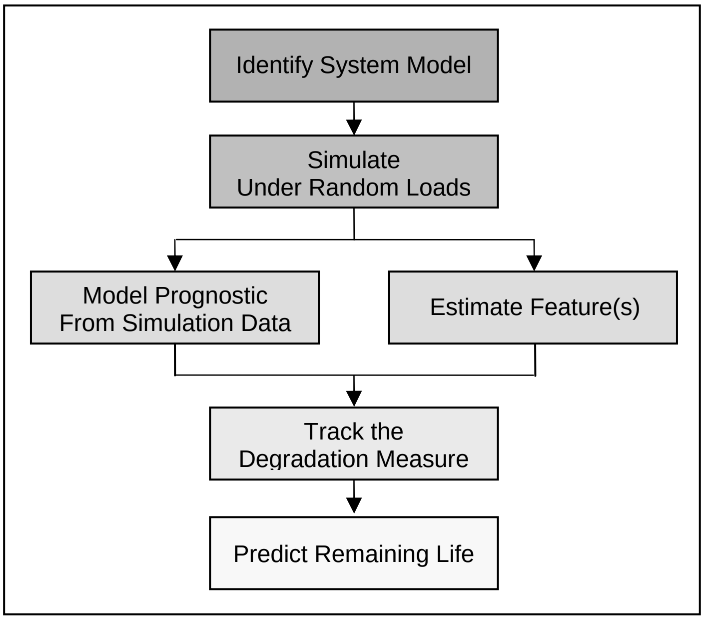
1. *Data Driven Prognostics:* The data driven approaches are derived directly from routinely monitored system operating data (e.g., calorimetric data, spectrometric data, power, vibration, acoustic signal, temperature, pressure, oil debris, and voltages). In many applications, measured input and/or output data is the major source for gaining a more intensive understanding of the system degradation behavior. The data driven approaches rely on the assumption that the statistical characteristics of data are relatively unchanged unless a malfunctioning event occurs in the system. In other words, the common cause variations are entirely due to uncertainties and random noise, whereas special cause variations (e.g., due to degradations) account for data variations not attributed to common causes. The data driven approaches are based on statistical and learning techniques from the theory of pattern recognition. The advantage of data driven techniques is their ability to transform high-dimensional noisy data into lower dimensional information for prognostic decisions. The main drawback of these approaches is that their efficacy is highly dependent on the quantity and quality of system operational data [390]. To illustrate, below are a few different approaches:

- Experience Based Prognostics: Within the maintenance framework, when a physical model of a subsystem or component is absent and there is an insufficient sensor network to assess condition, an experienced based prognostic model may be the only prognostic alternative. Experience based prognostics is the least complex one and requires the failure history or by design recommendations of the subsystem component under similar operation. Failure and/or inspection data is compiled from legacy systems and a statistical distribution is fitted to the data. Even though simple, but such a distribution can be used to drive interval based maintenance practices. An example may be the maintenance scheduling for an uncritical object that has little or no sensed parameters associated with it. In this case, prognosis of when the object will fail or degrade to an unacceptable condition must be based exclusively on analysis of past experience or OEM recommendations [105].

- **Evolutionary Prognostics:** An evolutionary prognostic relies on gauging the proximity and rate of change of the current component condition to known performance degradation or component faults. Evolutionary prognostics may be implemented on systems or subsystems that experience conditional failures such as compressor or turbine flow path degradation. Generally, evolutionary prognostic works well for system level degradation because conditional loss is typically the result of interaction of multiple components functioning improperly as a whole. This approach requires sufficient sensor information availability to assess the current condition of the system or subsystem and relative level of uncertainty in this measurement. Besides, the parametric conditions that signify known performance related faults must be identifiable. Moreover, while a physical model, such as a control system simulation, is beneficial, it is not a strict requirement for this technical approach [31], [450].

- **Feature Progression and AI Based Prognostics:** Utilizing known transitional or seeded fault degradation paths of measured or extracted features as they progress over time is another commonly utilized prognostic approach. In this approach, neural networks are trained on features that progress through a failure. In such cases, the probability of failure as defined by some measure of the 'ground truth' is required as priori information. The 'ground truth' information that is used to train the predictive network is usually obtained from inspection data. Based on the input features and desired output prediction, the network automatically adjusts its weights and thresholds taking into account the relationships between the probability of failure curve and the correlated feature magnitudes. The difference between a neural network output and the ground truth probability of failure curve is due to error that still exists. Therefore, the network parameters have to be optimized in order to minimize this error. Once trained, the neural network architecture can be used to intelligently predict the features progressions for a different test under similar operating conditions [653], [654]. Another alternative is a stochastic model. It can be used to evaluate the distribution of remaining useful component life as a function of uncertainties in component condition for a particular fault. The results from such a model can then be used to create a neural network or probabilistic-based autonomous system for real-time failure prognostic predictions [105].

2. *Model Based Prognostics:* The model based methods assume that an accurate mathematical model is available. The model based methods use residuals as features, where the residuals are the outcomes of consistency checks between the sensed measurements of a real system and the outputs of a mathematical model. The premise is that the residuals are large in the presence of malfunctions, and small in the presence of normal disturbances, noise and modeling errors. Statistical techniques are used to define thresholds to detect the presence of faults. The three main ways of generating the residuals are based on parameter estimation, observers (e.g., Kalman filters) and parity relations. The model based prognostics are applicable in situations where accurate mathematical models can be constructed from first principles [46].



A Simplified Model Based Prognostic Process

Figure B1 A model based prognostic process to predict remaining life of a system [390]

Adams proposes a model damage accumulation in a structural dynamic system as first/second order nonlinear differential equations [8]. Chelidze models degradation as a ‘slow-time’ process, which is coupled with a ‘fast-time’ observable subsystem; the model was used to track battery degradation of a vibrating beam system [123]. The strength of model based approach is the ability to incorporate physical understanding of the system to monitoring. Another merit claimed by Chelidze et al. is that in many situations, the changes in feature vector are closely related to model parameters [124]. Hence, it can also establish a functional mapping between the drifting parameters and the selected prognostic features. Furthermore, if understanding of the system degradation improves, the model can be adapted to enhance its accuracy and to address restrained performance problems. Consequently, it can significantly outperform data driven approaches.

Prognostics are considered as joint potentials to diagnostics; they assess the current health of a system and predict its remaining life, based on features that capture the gradual degradation in the operational capabilities of a system. Prognostics are vital to improve safety, plan successful missions, schedule maintenance, reduce maintenance cost and down time [95]. Contrasting the fault diagnosis, prognosis is a relatively new area and became an important part of Condition-based Maintenance. At present, there are many prognostic techniques; their use must be refrained and adjusted for each industry application. The prognostic methods can be classified as being associated with one or more of the following two approaches: Data driven and model based [126]. Each of these approaches has its own advantages and disadvantages, and, consequently they are often used in combination in many applications. Data driven prognostics can be also classified as experienced based, evolutionary and AI based prognostics [181], [390], [524]. Figure below represents an overlook of the current prognostic techniques and their related tools.

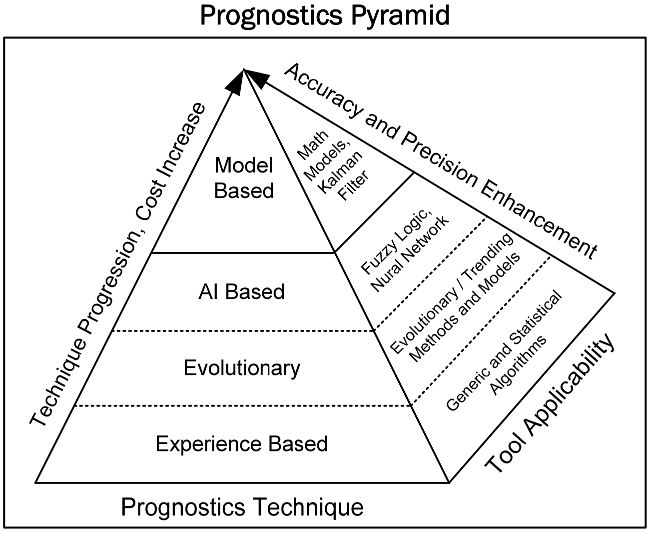


Figure B2 Different prognostic techniques and their related tool with consideration of their major characteristics

One approach to realize the implementation of different diagnostics and prognostics is through decision support systems, which are IT systems aiding in the decision making process. A human expert is needed to make the final decision and the system provides the required information for decision making. It can also be considered as a legal reason for using decision support systems instead of fully automated systems, e.g. if decision making is not time critical, but the consequences of a faulty decision is large. Nevertheless, it is essential to keep in mind that computer and IT systems can be reliable up to certain extent, they are often so complex that it is difficult to figure out the faults in their structures. A decision support system may have a number of diagnostic and prognostic tools, human experience and statistical data to provide the personnel with help in the decision making processes. In intelligent human computer collaboration both humans and computers takes initiative and action. Based on previous experience, the computer system may notice that a human operator tries to do something that may damage the equipment and intertwine. A dialogue between the system and the operator may result in a modified procedure, acceptable for both parts, which results in elimination of faults and also efficient and effective use of all resources [60].

Appendix C - Utilization of CBM in Industry

The acronym CBM, as previously mentioned, is associated with Condition Based Maintenance, a predictive maintenance tactic, which is adopted to monitor and diagnose the condition of the machinery and its components under investigation. Hence, it is possible to say that CBM is a technique of diagnosing failure mechanisms and making a prognosis of the remaining useful life before failure. This enables corrective maintenance action to be undertaken on the identified failing machinery or components at a time in advance of anticipated time of failure [269].

The use of CBM in manufacturing plants is discussed by many scholars such as Mobley [440], Tsang [630], Waeyenbergh et al. [643], Saranga [538], Yang [673], Bengtsson [59], Castanier et al. [114], and De Silva [155]. CBM is actually a maintenance process used to determine what must be done to ensure that a machinery system continues to operate as required. Within the CBM concepts, detection of any kind of flaw, contamination or wear is undertaken through various condition monitoring techniques and nondestructive tests of machinery components. Advances in engineering technologies provide integration opportunities for CBM systems, presenting further possibilities for increasing CBM system functionality. Of course, having an overview of how industry applies practices such as CBM in the work place offers valuable research results for CBM system stakeholders. As Higgs et al. claim, an international response confirms CBM to be a globally accepted maintenance practice [269].

CBM advances are impelled by industrial demands for improvements in: productivity, quality, inventory control, and expenditure on plant and machinery. Technological advances take place progressively as new scientific discoveries are made, accepted and applied to CBM systems. Recent technological advances include improved knowledge of material failure mechanisms and nondestructive tests, innovations in failure prediction techniques, new sensors and transducers, advancements in diagnostic and prognostic software, acceptance of communication protocols, developments in maintenance software applications and computer networking technologies. CBM system capabilities are assessed based on their ability to accurately diagnose failure conditions and then predict remaining working life before machine failure. Some of the comparatively recent trends can be briefed as followings:

- **Intelligent CBM:** The word intelligent entails the ability of understanding and making decisions without human intervention. There exist different technologies that provide such a capability, for example, smart sensors (i.e. sensors with built-in intelligence) capable of transmitting relatively rich and high-quality information [139], re-programmable on-line sensors, which are designed to be reconfigured with new rules in the events where detectable and recognizable patterns change [298], algorithms, fuzzy logic and neural networking, designed to analyze trends within recorded sensory data that can produce decisions on the likelihood of failure of monitored machinery [653], and eventually artificial intelligence algorithms capable of providing proxy data as a substitute for failing or a failed sensor [467]. Further benefits may be attained through integration of a CBM system with a company's computerized purchasing system, thus automating spare parts ordering [139].

- **Remote CBM:** Remote CBM Systems, unlike to localized ones which are independent predictive maintenance practices likely to be undertaken within immediate proximity of the components being monitored by a maintenance staff, are networked to another business systems and involve monitoring the condition of a component at a location away from the immediate vicinity of the component in question. Monitoring will be undertaken automatically or manually depending upon the systems features at intermittent periods. In addition, diagnostics of the machinery condition may be either automatic or manual, again depending upon the systems capabilities. Wireless sensors provide opportunities to locate them in difficult-to-reach places, electromagnetically noisy environments, and mobile applications where wire cannot be installed [684].

- **Internet CBM:** Exhibiting CBM data through web pages accessible by Internet browsers is given the name 'Internet CBM', or 'E-Monitoring Machine Health System' [269]. Internet CBM takes remote CBM to another stage, i.e. providing global remote capabilities. As browsers reside on many platforms, Internet CBM systems may be whilst away from the factory, i.e. overseas on business calls. Unauthorized access to an Internet CBM system can be prevented with the inclusion of user name and password access on the index web page for the web site. User name and password may be used to control access rights onto specific web pages and degree of user system interaction.

Kennedy et al. explains how interaction between users and the Internet CBM system is performed using Active Server Pages or ASPs [321]. ASPs, programmed using VBScript and JavaScript working behind the scenes within the Web server, offer flexibility to system designers. They carry out programmed instructions within the web server, define how the HTML is assembled and presented to users, providing users with the power to interact with the user interface and select his choice. Many measured variables regarding the condition monitoring and non-destructive inspection techniques may now easily be transmitted over the Web and presented to the end user as gauges, reporting the condition of the remote machine in real time. Further reading concerning the main components of a web based maintenance diagnostic system and methods of representing condition monitoring values onto a web site are discussed by Kunze in the year 2003 [352].

A survey was conducted by Higgs et al. in the year 2004 on CBM and condition monitoring systems in industry [269]. Answers and responses from a broad industrial representation over 15 different countries including the Americas, Europe, Japan, Australasia, Middle East and Africa were received and analyzed in this survey. From the incentives perspective, 95% of respondents either agree or strongly agree they introduced CBM to reduce the number of breakdowns and 83% of the respondents in the same way agree that their business adopted CBM to save money. Considering the production incentives, there were many comments indicating a strong production driven intuition for implementing CBM, mainly to increase output via better reliability, to enhance safety factor, to decrease shutdown and repair times, to eliminate secondary maintenance damages and finally to maximize utilization of investment and to offer uninterrupted production operation.

Regarding the technology and integration viewpoint, a majority of 62% of respondents use standalone CBM systems as opposed to 38% whose system is networked; furthermore, 63% of respondents indicate their organizations' CBM system is not connected to the Internet, as opposed to 37% whose system do have internet connectivity. Plus, 73% of respondents CBM systems do not integrate with a computerized failure diagnostic system, whereas 27% do. In addition, 67% of respondents organizations maintenance systems link directly with a computerized stock reordering system, as opposed to 33% whose systems do not [269]. Nonetheless, considering the most widely used condition monitoring techniques and nondestructive tests, the mentioned survey provides the results shown in the below table.

Table C1 Application broadness of different CMTs/NDTs in industry [269]

CMT/NDT	No. of Respondents	Related Percentage
Vibration Analysis	148	17.29%
Oil Analysis	113	13.20%
Infrared Thermography	99	11.57%
Human Inspection	92	10.75%
Motor Current Analysis	77	9.00%
Dye Penetrant Testing	74	8.64%
Ultrasonic Thickness Testing	73	8.53%
Ultrasonic Crack Detection	63	7.36%
Magnetic Particle Inspection	56	6.54%
Acoustics Emission Analysis	39	4.56%
Other *	22	2.57%

*Other CMTs/NDTs include: Wear Debris Analysis, X-ray Alloy Analysis, Strobe Light Inspection, Radiographic Testing, Air Testing, Ultrasonic Leak Detection, Laser Testing, Metallurgical Hardness Measurement and etc.

Appendix D - CMTs/NDTs ADAD Overview

Table D1a An overview of applicability, detectability, advantages and disadvantages of various CMTs/NDTs: **The ADAD Table**

CMT/NDT	Method	Applicability				Detectability		Advantages	Disadvantages
		Material		Object		Problem	Discontinuity		
Acoustic Emission Testing -AT-	NA	Concrete Ceramics FM/NFM Metals/Alloys Polymer-matrix Composites		➤Pipe ➤Tube ➤Gear ➤Tank ➤Valve ➤Shaft ➤Drum ➤Cable ➤Boom ➤Bullet ➤Turret ➤Wheel	➤Pinion ➤Sleeve ➤Nozzle ➤Vessel ➤Sphere ➤Bearing ➤Reactor ➤Gearbox ➤Adsorber ➤Regulator ➤Heat exchg.	➤Stress control ➤Leak detection ➤Bearing defect ➤Gear fault detection ➤Cavitation detection ➤Friction identification ➤Lubrication adequacy ➤Deformation detection ➤Crack initiation/growth ➤Fiber breakage finding ➤Material/turbulence flow	➤Crack ➤Pitting ➤Fatigue ➤Fracture ➤Porosity ➤Disbond ➤Inclusion ➤Impact wear ➤Delamination ➤Surface-breaking ➤Coating disbonding ➤Nonsurface-breaking	➤Defect localization ➤Portable equipment ➤Real-time monitoring ➤Sensitive to fine flaws ➤Earlier crack detection ➤Inaccessible zones are inspected as well ➤Independent of machine speed variation & structural resonances ➤Providing quantitative info on crack behavior	➤Skill/training is required ➤No detailed info on flaw type ➤Poor detection of misalignment/imbalance ➤Background noise can affect the test results ➤Cavitation may mask acoustic emission signs ➤AT analysis methods are not handy and easy
Electrical Inspection -EI-	**Dynamic Inspection**	➤Materials at the point of application of the test should be either conductor or allow some degree of magnetic flux seepage. But, the faulty machinery parts can be made of any material.		➤Fan ➤Belt ➤Gear ➤Shaft ➤Pump ➤Motor ➤Fitting ➤Flange ➤Circuit ➤Gasket ➤Bearing ➤Gearbox ➤Tooling machine ➤Electrical control unit		➤Rupture ➤Soft foot ➤Breakage ➤Imbalance ➤Looseness ➤Eccentricity ➤Over-heating ➤Misalignment ➤Excessive loading	The tests may indirectly result in identification of ➤Void ➤Crack ➤Erosion ➤Porosity ➤Corrosion ➤Surface-breaking	➤Real-time analysis ➤Energy cost savings ➤Portable equipment ➤Suitable for retesting ➤Automation potential ➤On-line testing method ➤High cost-effectiveness ➤Fast and reliable output ➤Easy-to-perform method ➤Early problem identification ➤Trending failure progression ➤No-part preparation required	➤Some skill required ➤Safety considerations ➤Some devices are expensive ➤Not very sensitive to some bearing problems
	Static Inspection			➤Wire ➤Cable ➤Motor ➤Circuit ➤Insulation		➤Rupture ➤Breakage ➤Eccentricity ➤Electrical short ➤Blocked circuit		➤Little skill required ➤Portable equipment ➤Relatively inexpensive ➤Easy-to-perform method ➤No-part preparation required	➤Off-line testing method ➤Supplementary tests needed to achieve reliable test results
Electromagnetic Testing -ET-	**Eddy Current Testing**	Generic Metals	Carbon Composites C/Epoxy Composites FM/NFM Metals/Alloys Metallic-matrix Composites	➤Drum ➤Roller ➤Cylinder	➤Bar ➤Nut ➤Bolt ➤Wire ➤Rivet ➤Cable ➤Sleeve ➤Flange ➤Strand ➤Fastener ➤Wire-rope ➤Clamping	➤Heat treatment proof ➤Crack identification in small localized areas ➤Damage detection in Carbon composites/epoxy ➤Conductivity test/measurement ➤Thickness measurement of thin materials/coatings	➤Void ➤Hole ➤Burst ➤Seam ➤Inclusion ➤Corrosion ➤Stress crack ➤Broken fiber ➤Delamination ➤Surface-breaking ➤Subsurface crack ➤Stress corrosion crack	➤Moderate speed ➤Reasonable cost ➤Immediate results ➤Portable equipment ➤Automation potential ➤Flaw sizing is possible ➤Sensitive to small flaws at or near material surface	➤Skill/training is required ➤Interference of rough surfaces with test ➤Only detects surface & subsurface flaws ➤Usually applicable to conducting materials ➤Object surface must be accessible to probe ➤For steel, used only for surface examination due to its high permeability
	Magnetic Flux Leakage Testing		Ferromagnetic Metals/Alloys		➤Pipe ➤Sleeve ➤Flange	➤Wall-thinning detection ➤Isolated pitting detection ➤Measurement of cross-sectional loss in wire-rope	➤Hole ➤Crack ➤Pitting ➤Corrosion ➤Surface-breaking	All above + ➤Relatively higher speed	All above + ➤Specimen must be magnetically saturated
	Remote Field Testing		Ferromagnetic Metals/Alloys		➤Pipe ➤Tube	➤Inspection of the whole wall thickness for cracks ➤Flaw detection on both inner & outer surfaces	➤Pitting ➤Corrosion ➤Impact wear ➤Stress crack ➤Stress corrosion crack	All above + ➤Equal detectability on inner & outer surfaces	All above + ➤Less sensitive when inspecting NFM metals

Table D1b An overview of applicability, detectability, advantages and disadvantages of various CMTs/NDTs: **The ADAD Table**

CMT/NDT	Method	Applicability		Detectability		Advantages	Disadvantages
		Material	Object	Problem	Discontinuity		
Laser Inspection -LI-	**Laser Alignment**	Glass Metals Generic Ceramics Polymers FM/NFM Metals/Alloys Polymer-matrix Composites	Bar Roll Pipe Bore Gear Shaft Lathe Pump Motor Pulley Spindle Bearing Vee Belt Flat Belt Gearbox Axial fan Actuator Coupling Sprocket Ventilator Web-roll sys. Toothed Belt	Leveling Imbalance Misalignment Precise positioning Flatness inspection	NA	High safety High accuracy High sensitivity Little skill required Energy cost savings Portable equipment Relatively inexpensive	NA
	Laser Holography		Bar Pipe Tube Plate Flange Bearing Cylinder Pressure vessel	Fluid flow analysis Rough surface flaws Stress/strain analysis Density measurement Static/dynamic displ. analysis	Crack Disbond Micro-crack Delamination Subsurface-breaking	High accuracy Relatively fast High sensitivity High flaw visibility Portable equipment Automation potential Non-contact technique Full-field view is possible	High skill required Relatively expensive Subjective interpretation of test results Advance data analysis required in locating internal defects
	Laser Profilometry		Pipe Joint Tube Boiler Cooler Nozzle Heater Furnace Generator Heat exchg.	Denting Swelling Weld inspection Diameter expansion Pipe/tube inspection	Crack Creep Pitting Erosion Corrosion Surface-breaking		
	Laser Shearography		Bar Pipe Tube Plate Flange Bearing Cylinder	Wrinkling Failed bonds Crushed core Internal corrosion Laminar separation Strain concentration Changes in bulkhead Changes in core splice	Void Crack Pitting Corrosion Delamination Impact damage Surface-breaking Disbond / Unbond		
	Laser Vibrometry		Fan Shaft Pump Motor Engine Bearing Damper Washing machine Gearbox Ventilator Alternator Generator Power tool Cooling sys. Compressor Transmission	Noise measuring Vibration measuring Machinery adjustment	Rotational fatigue	High sensitivity Portable equipment Automation potential Suitable for high RMSs Non-contact technique Real-time measurement Suitable for hot and light weight structures	Some skill required Relatively expensive
Magnetic Particle Testing -MT-	**Dry Particle Inspection**	Ferromagnetic Metals/Alloys	Pin Bar Nut Bolt Gear Rivet Billet Splice Vessel Fitting Sleeve Nozzle Sphere Linkage Actuator Fastener Tailstock Clamping Headstock	Near-surface crack detection/identification Crack detection at welded joints Crack removal proof in air-arc gouging	Burst Seam Creep Inclusion Cold shut Lamination Hole Pitting Corrosion Stress crack Surface-breaks Stress corrosion crack	Inexpensive Relatively fast Immediate results Portable equipment Easy-to-use equipment Fair training is required Sensitive to small flaws Detects both surface & subsurface flaws	Improper for bearing Coating may mask the sign Incapable of detecting internal flaws Require power supply for magnetization Preparation like sealant removal required Material may be burnt during magnetization Require magnetization and demagnetization
	Wet Suspension Inspection			Inspection of welds Small flaws on smooth surfaces Rough as-cast surface detection Environmental damage detection	Void Crack Hot tear	All above + Quick/easy cover of test item with particles Extra particle mobility for an extended time	All above + Not suitable to be used on rough surfaces
	Magnetic Rubber Inspection			Very fine flaw detection on smooth surfaces	Very fine cracks	All above + Inspection of difficult-to-reach zones	All above + Longer inspection time

Table D1c An overview of **a**pplicability, **d**etectability, **a**dvantages and **d**isadvantages of various CMTs/NDTs: **The ADAD Table**

CMT/NDT	Method	Applicability			Detectability		Advantages	Disadvantages
		Material	Object		Problem	Discontinuity		
Leak Testing -LT-	**Bubble Emission Leak Testing**	➤Object's material should not be reactive to the test liquid (e.g. water, oil, or any penetrant)	➤Pressurized systems	➤Coil ➤Pipe ➤Seal ➤Tube ➤Valve ➤Pump ➤Fitting ➤Flange ➤Gasket ➤Cylinder ➤Hydraulics ➤Condenser ➤Heat exchg.	➤Leak location ➤Rough leak rate ➤Structural integrity	➤Weld defect ➤Surface-breaking s through wall	➤High safety ➤Relatively fast ➤Most economical ➤Little skill required ➤Single side access ➤Easy-to-use methods	➤Low sensitivity ➤After-test cleaning ➤Sometimes is messy ➤Immersion BELT has test object size limit ➤Unable to locate inward directional cracks
	Chemical Reaction Leak Testing	➤Object's material should not be reactive to the tracer liquid or gas (e.g. ammonia) & liquid or powder colorimetric developers	➤Pressurized Systems with latent tracers (e.g. water, oil, ammonia and chlorine)	➤Pipe ➤Tube ➤Tank ➤Valve ➤Vessel ➤Cylinder ➤Container	➤Leak location ➤Seals integrity ➤Rough leak rate		➤Inexpensive ➤Relatively fast ➤Little skill required ➤Quite high sensitivity ➤Easy-to-use methods	➤After-test cleaning ➤Ventilation required ➤Sometimes is messy ➤Some safety concerns ➤Ammonia can corrode brass or copper objs.
	Gas Detection Leak Testing	NA	➤All objects containing various combustible or toxic gases		➤Leak severity ➤Leak location		➤No risk involved ➤No skill required ➤Immediate results ➤No test object size limit ➤Inspection of difficult-to-reach zones ➤Portable, easy-to-use & cheap equipment	➤Low sensitivity ➤Unable to provide exact leak rates
	Halogen Diode Leak Testing	➤Object's material should not contain explosive elements and it must not be in an explosive atmosphere or environment	➤All objects containing various halogen based fluids		➤Leak severity ➤Leak location	➤Surface-breaking s through wall	➤No skill required ➤Immediate results ➤Moderate sensitivity ➤No test object size limit ➤Inspection of difficult-to-reach zones ➤Portable, easy-to-use & cheap equipment	➤Safety concerns at high temperatures ➤Unable to provide exact leak rates
	Hydrostatic Leak testing	➤Object's material should not be reactive to water or any used penetrant or fluorescent tracers	➤Pressurized systems	➤Pipe ➤Tube ➤Tank ➤Valve ➤Container	➤Leak severity ➤Leak location	➤Weld defect	➤Quite inexpensive ➤Little skill required ➤Suitable for bulky object	➤Long test time ➤Low sensitivity ➤High pressure use ➤After-test cleaning ➤Sometimes is messy ➤Limited test object size ➤Paintings or insulation rise average test time
	Pressure Change Leak Testing	➤Object's material should not be reactive to the test gas		➤Tank ➤Cylinder ➤Container	➤Leak rate	NA	➤Low sensitivity ➤No test object size limit ➤Very accurate results on vessel-like objs only	➤Mobility ➤Long test time ➤Results depend on temperature and volume
	Radioisotope Leak testing	➤Object's material should not be reactive to the test solutions or the radioisotopes used		➤Pipe ➤Tube	➤Leak rate	NA	➤Very high sensitivity ➤No test object size limit ➤Inspection of difficult-to-reach zones	➤Safety concerns ➤Applicability limitations
	Tracer Gas Leak Testing	➤Object's material should not be reactive to the tracer gas	➤Vacuum systems ➤Pressurized systems ➤Small sealed objects	➤Pipe ➤Tube ➤Tank ➤Valve ➤Pump ➤Gauge ➤Cylinder ➤Radiator ➤Container ➤Condenser ➤Evaporator ➤Compressor	➤Leak location ➤Seals integrity ➤Exact leak rate	➤Surface-breaking s through wall	➤Rapid process ➤Short test time ➤Immediate results ➤Very high sensitivity ➤Some skill required ➤No temperature limit ➤Automation potential ➤Suitable for object with complex geometry	➤Mobility ➤Pre-test cleaning ➤TGLT is sensitive to background gases ➤Some safety issues ➤Calibration required ➤Expensive equipment
	Vacuum Flow Leak Testing	➤Object's material should not be reactive to the tracer gas	➤Various vacuum systems (e.g. vacuum furnaces & coaters, beam lines, laser process objs.)		➤Exact leak rate	NA		

Table D1d An overview of applicability, detectability, advantages and disadvantages of various CMTs/NDTs: **The ADAD Table**

CMT/NDT	Method		Applicability		Detectability		Advantages	Disadvantages
			Material	Object	Problem	Discontinuity		
Penetrant Testing -PT-	Fluorescent (Type I)	*Water Washable (Process A)*	Nonporous Materials: Metals Generic Ceramics Polymers FM/NFM Metals/Alloys Polymer-matrix Composites	➢Die ➢Rig ➢Bar ➢Rod ➢Axle ➢Pipe ➢Gear ➢Ring ➢Tank ➢Tube ➢Rope ➢Dryer ➢Billet ➢Shaft ➢Drum ➢Pump ➢Cable ➢Pinion ➢Sleeve ➢Wheel ➢Vessel ➢Fitting ➢Sleeve ➢Nozzle ➢Flange ➢Sphere ➢Reactor ➢Gearbox ➢Cylinder ➢Propeller	➢Flaw detection in bores and cored holes + All below	➢Void ➢Seam ➢Crack ➢Pitting ➢Erosion ➢Fatigue ➢Porosity ➢Hot tear ➢Inclusion ➢Corrosion ➢Cold shut ➢Shrinkage ➢Rolling lap ➢Forging lap ➢Lamination ➢Crater crack ➢Stress crack ➢Fatigue crack ➢Thermal crack ➢Corrosion crack ➢Surface-breaking	➢Relatively fast ➢Relatively cheap ➢High flaw visibility ➢Portable equipment ➢Relatively useable on rough surfaces ➢Suitable for inspection of complex designs	➢UV light required ➢Lower sensitivity ➢Unsuitable for retesting ➢Unsuitable for detection of shallow defects
		Post Emulsifiable (Process B/D)					➢Relatively fast ➢High sensitivity ➢High flaw visibility ➢Suitable for retesting ➢Suitable for inspection of shallow defects	➢UV light required ➢Relatively expensive ➢Rinsing aid required ➢Unsuitable for rough surfaces
		Solvent Removable (Process C)					➢Relatively fast ➢High flaw visibility ➢Heat drying not needed ➢Suitable for inspection of large part	➢Fairly expensive ➢Solvent required ➢UV light required
	Visible (Type II)	*Water Washable (Process A)*			➢Through-wall leak detection ➢Inspection of welds ➢Cavitation detection ➢Small flaw detection on smooth surfaces ➢Identification of 'lack of fusion' on welds ➢Flaw detection on both inner & outer surfaces		➢Inexpensive ➢Portable equipment ➢Inspection of large part ➢Relatively useable on rough surfaces ➢Apt for inspection of contaminated objects	➢Relatively slow ➢Lower sensitivity ➢Rinsing aid required ➢High manpower required ➢Unsuitable for detection of shallow defects
		Post Emulsifiable (Process B)					➢Moderate sensitivity ➢Suitable for detection of shallow defects	➢Relatively expensive ➢High manpower required
		Solvent Removable (Process C)					➢Portable equipment ➢Suitable for retesting ➢Used in remote fields ➢Suitable for inspection of large part	➢Relatively slow ➢Solvent required ➢Relatively expensive ➢Unsuitable for rough surfaces ➢Unsuitable for detection of shallow defects
Radiographic Testing -RT-	**Film Radiography**		Polymers Metals/Alloys Metallic-matrix Composites Polymer-matrix Composites ➢Materials with lower H content	➢Bar ➢Fan ➢Nut ➢Pipe ➢Joint ➢Tank ➢Tube ➢Rivet ➢Billet ➢Gear ➢Valve ➢Splice ➢Boiler ➢Pinion ➢Nozzle ➢Sleeve ➢Flange ➢Gasket ➢Bearing ➢Gearbox ➢Tailstock ➢Clamping ➢Headstock ➢Condenser ➢Heat exchg. ➢Transmission	➢Material integrity ➢Thickness variation	➢Lap ➢Void ➢Tear ➢Seam ➢Crack ➢Fatigue ➢Porosity ➢Cupping ➢Thinning ➢Inclusion ➢Cold shut ➢Core shift ➢Heat crack ➢Lamination ➢Incomplete Penetration ➢Delamination ➢Internal flake ➢Internal burst ➢Slag inclusion ➢Shrinkage crack ➢Shrinkage cavity ➢Stress corrosion ➢Corrosion pitting ➢Incomplete fusion	➢Relatively cheaper ➢Moderate resolution ➢Min part preparation	➢Relatively slow ➢Safety concerns ➢High skills required ➢Poor flaw positioning ➢2-side access required
	Digital Radiography				➢Material integrity ➢Fatigue check-up ➢Corrosion check-up		➢Very fast ➢Highest resolution ➢Portable equipment ➢Automation potential	➢Very expensive ➢High skills required
	Computed Radiography				➢Material integrity ➢Corrosion check-up ➢Casting inspections		➢High resolution ➢Moderate speed ➢Portable equipment ➢Suitable for field use ➢Environment friendly	➢Safety concerns ➢Quite expensive ➢High skills required ➢Longer process time ➢Longer exposure time
	Computed Tomography				➢Inspection of multi-layer parts		➢3D imaging ➢Very sensitive ➢Suitable for QC ➢High contrast/resolution	➢Mobility ➢Very expensive ➢Time consuming ➢High skills required
	Neutron Radiography		Ceramics All Metals/Alloys Polymers/Plastics Carbon Composites C/Epoxy Composites Metallic-matrix Composites ➢Material with higher H content		➢Radioactive objects inspection ➢Hydrogen content measurement ➢Alignment check of internal parts		➢Suitable for QC ➢Suitable for composite materials ➢Very sensitive to certain elements	➢High skills required ➢Relatively expensive
	Neutron Radioscopy				➢Imaging processes/equipment ➢Visualization of liquid/gas flow inside metallic components		➢High image contrast ➢Short exposure time ➢Good image linearity	➢Quite expensive ➢High skills required ➢Poor image resolution
	Neutron Tomography				➢Hydrogen content measurement	various surface and internal flaws can be very good detected, except laminar flaws	➢3D imaging ➢High contrast/resolution	Same as CT

Table D1e An overview of applicability, detectability, advantages and disadvantages of various CMTs/NDTs: **The ADAD Table**

CMT/NDT	Method		Applicability		Detectability		Advantages	Disadvantages
			Material	Object	Problem	Discontinuity		
Stress Wave Analysis -SA-	NA		Metals Generic Ceramics FM/NFM Metals/Alloys	➤Bar ➤Joint ➤Tube ➤Plate ➤Shaft ➤Valve ➤Pump ➤Motor ➤Flange ➤Engine ➤Bearing ➤Cylinder ➤Gearbox ➤Axial fan ➤Thruster ➤Generator ➤Gas turbine ➤Compressor ➤Propulsions ➤Transmission	➤Skidding ➤Cavitation ➤Imbalance ➤Misalignment ➤Improper assembly ➤Looseness/fracture ➤Fluid contamination ➤Lubricant degradation	➤Crack ➤Pitting ➤Fatigue ➤Spalling ➤Disbond ➤Abrasion ➤Corrosion ➤Impact wear ➤Delamination ➤Impact damage ➤Surface-breaking	➤High safety ➤High sensitivity ➤Little skill required ➤Real-time analysis ➤On-line testing method ➤Fast and reliable output ➤Early problem identification ➤Trending failure progression ➤Low incidence of false alarm ➤No-part preparation required	➤Mobility ➤Quite expensive ➤Depth of defect is unknown
Thermal Inspection -TI-	**Passive Thermography**		Metals Generic Ceramics FM/NFM Metals/Alloys Polymers/Composites	➤Fin ➤Bar ➤Fan ➤Rod ➤Bus ➤Kiln ➤Belt ➤Pipe ➤Gear ➤Fuse ➤Ring ➤Tank ➤Tube ➤Rope ➤Billet ➤Dryer ➤Shaft ➤Drum ➤Cable ➤Roller ➤Pump ➤Motor ➤Boiler ➤Piston ➤Splice ➤Clamp ➤Pinion ➤Circuit ➤Wheel ➤Blower ➤Vessel ➤Sleeve ➤Fitting ➤Switch ➤Sleeve ➤Nozzle ➤Flange ➤Sphere ➤Turbine ➤Breaker ➤Reactor ➤Bearing ➤Furnace ➤Gearbox ➤Cylinder ➤Winding ➤Coupling ➤Adsorber ➤Propeller ➤Brushing ➤Capacitor ➤Regulator ➤Generator ➤Connector ➤Lighting panel ➤Power transformer ➤Heat exchg.	➤Misalignment ➤Leak detection ➤Insulation failure ➤Excessive friction ➤Improper brushing ➤Bearing lubrication ➤Failing transformer ➤Loose elect. contacts ➤Motor/pump overload ➤Short/overload circuit ➤Overheating/induction	➤Void ➤Crack ➤Cavity ➤Pitting ➤Erosion ➤Fatigue ➤Porosity ➤Disbond ➤Inclusion ➤Adhesion ➤Corrosion ➤Lamination ➤Impact wear ➤Delamination ➤Core damage ➤Water entrapment	➤Ease of use ➤Inexpensive ➤Relatively fast ➤Highly portable ➤Immediate results ➤No-contact technique ➤Large area inspection ➤Fair training is required	➤Less quantitative accuracy ➤Sensitive to ambient conditions ➤Results influenced by variation of emissivity ➤Result's quantitative analysis requires skill
	Active Thermography	***Pulsed Thermography***			➤Thin materials/coatings thickness measurement ➤Identification of size, depth, thermal resistance of defects		➤Relatively fast ➤Ease of use in the field ➤Provide info about size, depth and thermal resistance of defects	➤Results influenced by variation of emissivity ➤Difficult to deposit large amount of energy in short time over large surface
		Transient Thermography			➤Deep-seated defect detection in low temp. conductive materials		➤Relatively fast ➤Easy to interpret results ➤Large areas for both near surface & surface defects can be inspected	➤Result dependent on size/depth of defects ➤Difficult to deposit large amount of energy in short time over large surface
		Step Heating Thermography			➤Thin materials/coatings thickness measurement ➤Thermal conductivity test		➤Relates variation of surface temp with time to specimen features	➤Difficult to deposit large amount of energy in short time over large surface
		Modulated Thermography			➤Identification of size, depth, thermal resistance of defects		➤Better depth resolution ➤Higher image resolution ➤Suitable for inspection of heat-sensitive objects ➤Low increase of object's surface temp required	➤Complicated set-up ➤Insensitive to variation of emissivity & non-uniform heating ➤Unsuitable for detection of deep defects
		Pulse Phase Thermography			➤Thin materials/coatings thickness measurement ➤Identification of size, depth, thermal resistance of defects		➤Relatively fast ➤Ease of use in the field ➤Better depth resolution ➤Higher image resolution	➤Complicated set-up ➤High increase of obj. surface temp required ➤Difficult to deposit large amount of energy in short time over large surface
		Microthermography			➤Quality/integrity assessment of coatings		➤Provide info about near-surface defects	➤Relatively slow ➤High skill required
		Vibrothermography			➤Defect severity & distribution ➤Evaluation of stress distribution ➤Identification of complex damage ➤Evaluation of quality of bondings ➤Thickness evaluation of thin materials/coatings		➤High sensitivity in detection of small & tightly closed cracks	➤High skill required

Table D1f An overview of applicability, detectability, advantages and disadvantages of various CMTs/NDTs: **The ADAD Table**

CMT/NDT	Method	Applicability			Detectability		Advantages	Disadvantages
		Material	Object		Problem	Discontinuity		
Tribological Testing -TT-	**Contamination Analysis**	Oils Greases Lubricants	➢Valve ➢Motor ➢Chiller ➢Engine ➢Turbine ➢Cylinder ➢Hydraulics ➢Compressor ➢Transmission ➢Hot oil system	➢Cam ➢Tank ➢Pump ➢Vessel ➢Bearing ➢Gearbox ➢Reducer	➢Identification of external sand, dirt, fiber s and debris ➢Measurement of lubricant degradation ➢Detection of wear debris and particles ➢Identification of a coolant leakage ➢Evaluation of overall machinery condition	➢Wear ➢Abrasion ➢Adhesion ➢Corrosion	➢No object preparation ➢Automation potentials ➢Extremely cost-effective ➢No serious safety hazard ➢Accurate and permanent test record	➢Equipment are relatively expensive ➢Sometimes is messy ➢Lab based procedure ➢Not-instantaneous evaluations and results ➢Acquisition of accurate oil samples are critical
	Oil Analysis			➢Tank ➢Container	➢Oil quality control ➢Measurement of water/liquid content ➢Control usability of an oil or lubricants	NA		
	Wear Analysis			➢Seal ➢Cam ➢Gear ➢Ring ➢Shaft ➢Pump ➢Bearing ➢Gearbox ➢Reducer ➢Bushing	➢Identification of degraded component ➢Identification of root cause of wear course ➢Evaluation of overall machinery condition	➢Wear ➢Erosion ➢Fatigue ➢Fretting ➢Abrasion ➢Adhesion ➢Corrosion ➢Cavitation		
Ultrasonic Testing -UT-	**Lamb Waves Inspection**	Metals Generic Ceramics Polymers FM/NFM Metals/Alloys Polymer-matrix Composites	➢Bar ➢Fan ➢Nut ➢Bolt ➢Seal ➢Gear ➢Joint ➢Rivet ➢Billet ➢Valve ➢Pump ➢Motor ➢Boiler ➢Sleeve ➢Flange ➢Gasket ➢Bearing ➢Gearbox ➢Pothead ➢Fastener ➢Tailstock ➢Insulator ➢Conveyer ➢Condenser ➢Headstock ➢Heat exchg. ➢Compressor	➢Pipe ➢Tube ➢Tank ➢Roller ➢Vessel	➢Inspection of welds ➢Fluid leakage detection ➢Thickness measurement of plates & sheets	➢Burst ➢Crack ➢Pitting ➢Fatigue ➢Erosion ➢Porosity ➢Corrosion ➢Lamination ➢Stress crack ➢Fatigue crack ➢Stress corrosion crack	➢Immediate results ➢Portable equipment ➢Relative ease of use ➢Automation potential ➢Little part preparation ➢Very sensitive to fine planar type flaws ➢Applicable to a wide range of materials ➢Applicable only for thick material plates	➢High skill is required ➢Couplant is required ➢Interference of rough surfaces with test ➢Calibration blocks/ref. standards required ➢Incapable of detecting defects whose plane is parallel to sound beam
	Pulse-Echo Inspection			➢Components with complex geometry	➢Bearing wear trending ➢Fluid leakage/caulking ➢Pressure/vacuum leak ➢Thickness measurement ➢Estimation of greasing time ➢Estimation of greasing amount ➢Broken, crushed or corroded core ➢Lubrication condition assessment	➢Erosion ➢Porosity ➢Disbond ➢Inclusion ➢Corrosion ➢Stress crack ➢Delamination ➢Fatigue crack ➢All primary flaws ➢Stress-corrosion crack	➢Immediate results ➢Portable equipment ➢Identifies small flaws ➢Automation potential ➢Little part preparation ➢Applicable to objects with thick & thin plates ➢Provides information on depth/size of defect ➢Determines which side of a wall has no flaw	➢High skill is required ➢Couplant is required ➢Interference of rough surfaces with test ➢Inspection from both sides are required ➢Applicable to limited variety of thicknesses ➢Less effective on multi-layer/skin structures
	Tip-Diffraction Inspection			➢Tank ➢Vessel ➢Nozzle	➢Inspection of welds ➢Exact sizing of flaws ➢Crack growth monitoring	➢Crack ➢Porosity ➢Fracture ➢Corrosion ➢Inclusion ➢Stress crack ➢Delamination ➢Fatigue crack ➢All primary flaws ➢All secondary flaws	➢Immediate results ➢Portable equipment ➢Automation potential ➢Little part preparation ➢Applicable to multi-layer plates/structures ➢Detect flaws on either side of the structure ➢Applicable to objects with thick or thin walls	➢High skill is required ➢Couplant is required ➢Slow inspection speed ➢Does not determine layer position of flaw ➢Accurate alignment of search unit is critical ➢Access to both sides of the item is required

Table D1g An overview of applicability, detectability, advantages and disadvantages of various CMTs/NDTs: **The ADAD Table**

CMT/NDT	Method	Applicability		Detectability		Advantages	Disadvantages
		Material	Object	Problem	Discontinuity		
Vibration Analysis -VA-	**Free-vibration Analysis**	Metals Generic Ceramics FM/NFM Metals/Alloys	➢Fan ➢Belt ➢Gear ➢Shaft ➢Rotor ➢Mixer ➢Roller ➢Pump ➢Motor ➢Chiller ➢Sleeve ➢Blower ➢Spindle ➢Turbine ➢Bearing ➢Gearbox ➢Tailstock ➢Headstock	➢Imbalance ➢Turbulence ➢Misalignment ➢Plastic deformation ➢Improper lubrication ➢Resonance problems ➢Evaluation of tool life ➢Loosened assemblies ➢Inspection of tool wear ➢Flow-induced problems	➢Crack ➢Fatigue ➢Corrosion ➢Deformation ➢Impact wear ➢Stress crack ➢Fatigue crack ➢Corrosion crack ➢Surface-breaking	➢Safe technique ➢Highly sensitivity ➢Immediate results ➢No part preparation ➢Portable equipment ➢Provide detailed info ➢Real time monitoring ➢Fast & reliable output ➢Easily integrated with other CMTs/NDTs	➢Sensitive to noise ➢High skill required ➢Relatively expensive ➢Complicated analysis ➢Baseline data required ➢Speed variation of parts that move affects test results and assessment
	Forced-vibration Analysis		➢Stationary structures	➢Flaw & discontinuity detection & evaluation		➢Safe technique ➢Highly sensitivity ➢No part preparation ➢Fast & reliable output ➢Easily integrated with other CMTs/NDTs	➢High skill required ➢Relatively expensive ➢Complicated analysis ➢Baseline data required
Visual/Optical Inspection -VI-	**Eye-Mirror-Flashlight Inspection**	All	All	➢Leak detection ➢Misalignment detection ➢Overall machinery condition ➢Identification of excess heat, vibration & noise ➢Surface inspection of objects	➢Hole ➢Crack ➢Blister ➢Fracture ➢Corrosion ➢Impact wear ➢Deformation ➢Surface-breaking	➢Minimum cost ➢Highly portable ➢Immediate results ➢No part preparation ➢No extensive training ➢Least skill is required ➢Applicable to all kinds of materials/objects	➢Requires good lighting ➢Requires good eyesight ➢Limited to surface inspection of objects ➢Misinterpretation of scratches is possible ➢Only relatively large flaws can be identified
	Borescopic Inspection			➢Inspection of internal & external parts of objects		➢Fair equipment cost ➢Inspection of difficult-to-reach zones	➢Only surface flaws can be found

Appendix E - CMTs/NDTs Technical Advancements

a. Acoustic Emission Testing

AT instruments and noise detectors are used to detect changes and monitor conditions in mechanical, electrical, and process systems. There are many acoustic emission (AE) development and manufacturing companies active in the world today. To illustrate, Vallen Systeme based in Munich - Germany develops and produces high-tech instrumentation for different acoustic emission applications. Its product line comprises large digital multi-channel systems, advanced acoustic emission software, analog front-end modules, handheld device, and acoustic emission sensors. On the other side of the Atlantic, Physical Acoustic Corporation based in Princeton - New Jersey is also very advanced in manufacturing of AT instruments, specially the portable ones, plus acoustic emission analysis software.

Vallen AMSY-5 AE System

Figure E1 A multi-channel system for acoustic emission detection and analysis [WS102].

A Hand-Held AE Instrument

Figure E2 A hand-held instrument and some sensors for AE measurement and leak detection [WS73]

In the scaffold of machine condition monitoring (CM), AT provides a reliable way of detecting energy-loss processes such as friction and impacts that are related to mechanical degradation. Many inspection techniques detect such processes when they are macroscopic, for example, by tripping an unusual increase of temperature via thermography, the ultimate goal of CM is to detect them at a much earlier stage and AT facilitates reaching this goal. Holroyd Instruments in Derbyshire - U.K. produces handy AT tools known as Machine Health Checkers which provide an easy use this valuable technique.

AE Machine Health Checker

Figure E3 Two different types of AE instruments for machine condition monitoring [WS50]

b. Electrical Inspection

Electric inspection (EI) instruments and techniques are more and more utilized to assess and monitor the condition of various electrical devices and predominantly motors. Since the beginning of 21st century, with increasing energy costs and environmental concerns, the importance of EI has become more vivid taking into account its major role in boosting motors efficiency, diminishing electrical equipment faults and their detrimental by-products such as heat. Besides, it has been practically attested that monitoring electrical equipment's performance and making necessary adjustments improve their reliability, extend the life of the equipment and reduce the overall operating cost of the facility. Particularly for motors, electrical inspection has been proven to be cost effective, as it reduces the number of unplanned shutdowns due to premature motor failure and reduces the amount of motor repairs and replacements.

There are different companies round the world which produce EI instruments and perform condition monitoring of motors and other electrical equipment. One of the leading companies in this field is PdMA Corporation with its corporate office in Tampa, FL, U.S.A. and many representatives in North and South America, Europe, Asia and Africa. The company has three major products. The first is an instrument branded as E_{MAX} which performs dynamic inspection on motors without interrupting production processes. It can be used for motor current signature analysis and process analysis through captured provides voltage, power, and efficiency data.

The second is a motor circuit evaluator (MCE) that undertakes an inclusive static inspection off-line. MCE undertakes detailed analyses of motor and circuit conditions in as little as three minutes. Analysis of the motor and associated circuits via this instrument allows for the detection of electrical faults in power circuit, insulation, stator, rotor, and air gap fault zones. Established baseline readings can be stored and recalled after subsequent testing to produce trend data and comparisons. Eventually, the third is an instrument branded as MCE_{MAX} which executes both dynamic and static inspections and determines the condition of the motor and its associated power circuit in a short period of time.

PdMA Devices for Dynamic and Static Motor Inspection

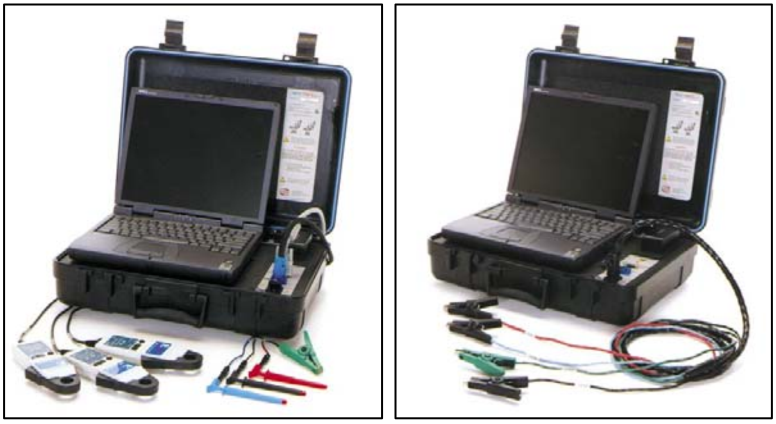


Figure E4 Photos of E_{MAX} dynamic inspection device (left) and MCE static inspection device (right) [WS74]

It has to be added that such devices can be exploited on all applications and motors regardless of size, type, or condition. The devices are portable, lightweight, and battery operated allowing for inspection of motors and starters on in the field and immediate creation of reports. E_{MAX} performs torque and efficiency analyses in addition to current signature and power quality analysis on low, medium and high voltage motors. MCE is able to run variable test voltages from 250 to 5000 V, measures insulation resistance up to 3 TΩ, carry out precision resistance measurements from 10 μΩ to 2000 Ω using. Moreover, both devices incorporate comprehensive software for data management which has advanced reporting functions. The reports include a series of graphs, screen plots and historical comparisons. These reporting capabilities clearly illustrate the status of rotors, stators, power quality and other fault zones which facilitates identifying and assessing possible problems before they result in lost productivity from forced downtime.

c. Electromagnetic Testing

Eddy current (EC) devices exist in a wide range for a variety of applications. In recent years, there has been a jump in production of such equipment. Nowadays, different hi-tech EC instruments with specific features can be purchased for reasonable prices. One of the leading companies in producing these tools is GE Inspection Technologies. As an example, two different types of its products are shown below.

Eddy Current Instruments

Figure E5 An image representing different portable EC tools. From left to right: a dual frequency EC instrument for crack and corrosion detection, a single frequency EC tool for crack and corrosion detection with conductivity and coating measurement [WS44]

Magnetic flux leakage (MFL) instruments are quite similar to EC ones, but with its specific probes. Magnetic flux leakage is based on the magnetization of the material to inspect using a strong magnet located inside the probe. As the probe encounters a wall reduction or a sharp discontinuity, the flux distribution varies around that area and is detected either with a Hall-effect transducer or with an inductive-pickup coil. Nevertheless, in recent years some innovative systems have been designed for specific applications such as inspection of the inner and outer surfaces of pipes, tubes and bars.

Magnetic Flux Leakage Probe

Figure E6 A picture representing the conceptual design and an actual probe used in MFL testing [WS71]

Examples of Innovative Magnetic Flux Leakage Systems

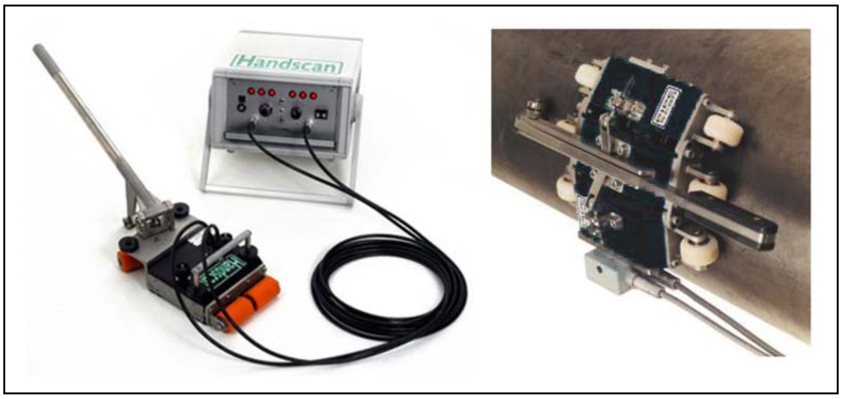


Figure E7 An image showing three different portable MT kits. From left to right: Handscan MFL system used to detect corrosion on floor and plate-wall structures, Pipescan MFL system used to detect corrosion on pipes with approximate diameter range of 1- 38 cm [WS110]

Instruments used for remote field testing (RFT) are often dual use EC/RFT instruments employing multi-frequency technology. Indeed, RFT is a variation of the EC send-receive probe technique. The exciter coil is separated from the receiver coils by a distance equivalent to two or three times the tube outer diameter. The receiver coils sense the flux lines that cross the tube wall twice. Commonly, RTF is used for the inspection of ferromagnetic tubing such as carbon steel and ferrite stainless, as well as for the detection and sizing of wall thinning resulting from corrosion, erosion, wear, pitting, and baffle cuts. Specifically made RTF probes can be used effectively for inspection of heat exchangers, feed water heaters, boiler tubes, and buried pipes.

Remote Field Testing Probe

Figure E8 A picture representing the conceptual design and two actual probes used in RFT testing. The upper one is dual exciter used for inspection of tubes and the lower one is specifically designed for inspection of boilers (Adapted and retrieved from *www.olympusndt.com* in February 2008).

d. Laser Inspection

Since 1990s, laser inspection has been increasingly utilized in manufacturing and processing industries as the production and maintenance managers become more and more familiar with its various applications which result in significant cost savings. As one of the most important LI methods, laser alignment is exceptionally recommended to be utilized in industries where potential machinery misalignments my increase number of failures and thus the downtimes or raise the energy consumption by certain equipment. In fact, correct machine alignment is essential to sustain smooth operations and high product quality, to ensure that machines are correctly positioned, and to correct those that are not during machine installation, when commissioning machines, after refitting and after repairs. One of the world's leading companies in designing and producing laser alignment systems for industrial maintenance and quality assurance is Prüftechnik AG which has been founded and headquartered in 1972 in Ismaning, Germany. The company has 13 regional sales and service offices in Germany and Austria plus 14 subsidiaries in North and South America Europe and Asia. Its different laser alignment systems are utilized for shaft alignment, bore and bearing shell alignment, straightness and flatness measurement, roll parallelism measurement and also accurate monitoring of positional changes.

Different Laser Alignment Systems and Their Applications

Figure E9 Photos of different laser alignment systems and their applications in industry. From left to right: a modular mid-range shaft alignment system, a bore alignment system, a flatness and level measurement system, a pulley and belt-drive alignment system [WS82]

Another example of laser inspection equipment is shearography systems. Shearography can be used both during initial manufacture and later for in-service inspection of materials for internal and external surface discontinuities. This method offers rapid and unique inspections. A leading company in development and production of industrial shearography systems and techniques is Dantec Dynamics A/S which has its headquarter in Skovlunde, Denmark but operates worldwide through various distributers in Ulm, Germany as well as 24 other countries in North and Latin America, Europe and Asia Pacific. Dantec Dynamics' laser inspection technologies offer four varieties of equipment and software for industrial shearography, two of which are introduced below. Before, it has to be expressed that although use of shearography in industry is still limited in comparison with other nondestructive tests like ultrasonic testing, but the demand for a much faster full field method without surface preparation or use of couplant generates the need for better and faster techniques for nondestructive inspection. Consequently, this contributes to growth of various shearographic applications in different industries.

Figure E10 shows Dantec Dynamics' Q800 and Q810 shearography instruments which are non-contact and full-field, compact and completely portable systems that can detect defects such as cracks, delaminations, disbonds, kissing bonds, wrinkling, impact damage, and separation of structural components and bond lines in carbon fiber, glass fiber, reinforced plastics, laminates, honeycomb structures, foams, woods and metals. The inspection results are displayed live to the operator allowing an early evaluation to be undertaken. It is featured by advance image processing to be used for image export and reporting. Typical surface inspection times of various specimens are 10 to 30 seconds to cover areas from a few millimeters square up to several meters square in a single inspection.

The Q-800 system incorporates a miniaturized shearography sensor with integrated high resolution CCD camera and various shear optics. Illumination is provided by a diode laser array and the whole system is controlled from a laptop or a desktop computer. The sensor can be mounted on a tripod or a fully automatic robotic inspection system for quality control purposes. The system can be operated in daylight conditions using the standard laser diode array. The system employs a highly sensitive interferometric technique which measures microscopic surface deformations caused by internal flaws when a small loading is applied to the object via thermal, pressure, vibration or mechanical excitation. The results are displayed real-time as the material responds to the excitation and are easily interpreted by the operator. The Q-810 system has the similar features to the Q-800 system but with a full-field inspection rate is of 30 cm x 20 cm every 10 seconds. Besides, with adaptive seals the systems can be used on flat as well as highly curved surfaces. It is suitable for defect detection in composite materials over large surface areas, in tough field environments.

Portable Shearography Systems

Figure E10 Two portable industrial shearography systems made by Dantec Dynamics for non-contact and full-field inspection of material surfaces: Q-800 system on the left and Q-810 system on the right [WS30]

e. Leak Testing

Leak testing (LT) instruments and techniques are used to locate leaks and measure leak rates on industrial machinery and equipment. During the past 20 years improvements were mainly in size, handling and automation. Today, leak testing devices are robust, easy to use and offering a large range of sensitivity. There are many companies which produce different types of LT equipment, some of which have already named. An active company producing LT solutions used for BELT is Contesco Corporation which has different facilities in U.S.A. and also in Antwerp, Belgium. It produces gas LT solutions which are nontoxic, oxygen and hydrocarbon friendly nonreactive, and temperature compatible.

Gas Leak Testing Solution

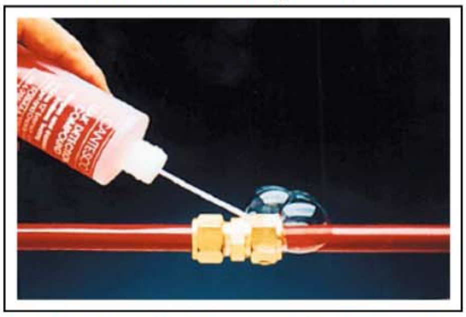


Figure E11 A gas leak detection solution [WS28]

Among all the instruments available for leak testing one should not neglect the application of handheld, mobile, and wireless and cable fixed devices used for leak detection of different gases. This cannot only save money by preventing material loss, but ensures a certain level of safety in each plant. One of the companies well known in this sector is Dräger Safety AG which is headquartered in Lübeck, Germany.

Stationary and Handheld Detectors for Toxic and Combustible Gases

Figure E12 Photos of, from left to right, stationary toxic gas leak detectors, stationary combustible gas leak detectors, and a handheld multi gas leak detector [WS32]

In recent years, there have been dramatic advancements in the field of TGLT equipment. Small portable mass spectrometers are examples of these developments. PICO, a helium mass spectrometer, made by MKS Instruments, Inc. which has headquarter in Andover, MA, U.S.A. PICO has sensitivity below $1x10^{-10}$ std.cm^3/s for a weight of 7.7 kg and dimensions of 10x28x39 cm.

A Portable Helium Mass Spectrometer Used for LT

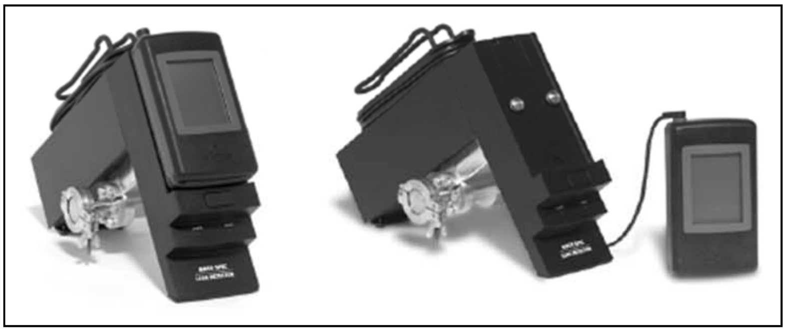


Figure E13 A portable helium mass spectrometer used in tracer gas leak testing [WS64]

f. Magnetic Particle Testing

Magnetic particle testing is a nondestructive inspection technique used for detection of surface and subsurface flaws in ferromagnetic materials are materials that can be magnetized to a level that will allow the inspection to be effective (e.g. iron, nickel or cobalt, or some of their alloys). MT is used to inspect a variety of product forms such as castings, forgings, and weldments. In recent decades, this test has been more and more used in industry. Although, previously there were only stationary MT equipment to be used but advancement of science and technology has brought the ease of use and mobility for this test as well.

One of the leading companies in production of MT tools and equipment is Magnaflux, a division of Illinois Tool Work Inc. This company fabricates different mobile MT kits (i.e. wet particle inspection kit with fluorescent magnetic particles and black light, and dry one with non-fluorescent particles) and a variety accompanying materials and equipment.

Portable Magnetic Particle Testing Kits

Figure E14 Three different portable MT kits. From left to right: Magnetizing yoke kit used for dry particle inspection, similar kit with battery powered yoke, and dry particle inspection kit with black light which requires a magnetizing yoke in addition [WS61]

g. Penetrant Testing

Penetrant testing (PT) is the descendant of the old 'oil and whiting' method formerly used by the railroad industries in 1920s. PT was perked up by Robert and Joseph Switzer in 1941 when they discovered that the addition of visible and fluorescent dyes to the Penetrant greatly improved the technique. Since then, continuous development efforts in this field have led to current improved PT techniques and materials. PT equipment and materials are used to detect surface defects and leakages of different machinery parts. There are many PT development and production companies active in the world today. One of the leading companies in production of PT equipment and materials is Magnaflux, a division of Illinois Tool Work Inc. This company fabricates different mobile PT kits, a few stationary PT units and a wide variety of accompanying materials and equipment.

Portable Penetrant Testing Kits

Figure E15 Three different portable PT kits. From left to right: visible PT kit incl. penetrant, developer and cleaner sprays, wiping cloths and hand towel; a general purpose visible PT; a fluorescent PT kit with UV light [WS62]

The configuration of PT stationary units or systems varies based on the PT method used. For example, a PT stationary unit which has been designed for post emulsifiable lipophilic method (method B) has eight stations as follows: penetrant station, drain station, emulsifier Station, rinse station, drain station, dryer station, developer station and eventually inspection station. Or, a PT stationary unit which has been designed for post emulsifiable hydrophilic method (method D) has nine stations as follows: penetrant station, drain station, pre-rinse station, drain station, remover station, rinse station, dryer station, developer station and inspection station. It is essential to restate that the choice of penetrant method highly depends on the level of sensitivity required, number of parts to be tested, surface condition of part being inspected, configuration and material of the test specimen and availability of water, electricity, suitable testing area and etc.

Water Washable PT Stationary Unit

Figure E16 A PT stationary unit designed for water washable method with six different stations: penetrant station, drain station, wash station, dryer station, developer station and inspection station [WS62]

h. Radiographic Testing

Radiography is a nondestructive test that examines the volume of a specimen. Radiography uses x-rays and gamma-rays to produce a radiograph of a specimen, showing any changes in thickness, defects (internal and external), and assembly details to ensure optimum quality in the operation. In order to meet the constantly changing demands of industry, various new sources of radiation, such as neutron generators and radioactive isotopes, are continually being developed. Other ongoing advances also include improved x-ray films and automatic film processors, as well as improved or specialized radiographic techniques. However, with today's technology it is now possible to generate images of higher quality and sensitivity. The higher quality of radiographic images is primarily due to improved films that have a wider variety of available grain sizes. Also, with the addition of computers and other advanced electronic systems to the process, the advent of digital radiography has proved to be a large advancement within the industry. With the use of digital radiography, a radiographic image captured today can theoretically be preserved forever and sent anywhere in the world almost instantly.

One of the leading companies in development and production of industrial radiographic equipment and techniques is GE Sensing and Inspection Technologies which operates worldwide and have production plants and sales offices in Germany (i.e. in Alzenau, Ahrensburg, Hechingen and Hürth) as well as in Belgium, China, France, Hong Kong, Japan, Slovakia, U.K. and U.S.A. GE Sensing and Inspection Technologies offers a wide variety of equipment and software for radiographic testing in industry. It has to be expressed that although use of RT in industry is still limited in comparison with other nondestructive tests (especially in manufacturing and processing industries), but the rapid development of robust, smaller and safer equipment continually contributes to growth of various RT applications in numerous industries.

Portable, Mobile and Stationary X-ray Instruments for Industrial RT

Figure E17 A variety of modern industrial x-ray systems [WS43]

Portable and Stationary Computed Radiography Systems for Industrial RT

Figure E18 A variety of modern industrial x-ray systems [WS43]

i. Stress Wave Analysis

The threat of plant interruptions in today's manufacturing environment is increasingly seen as the number one risk when trying to optimize production and quality while at the same time minimizing maintenance expenses. To meet growing production demands with current equipment and facilities while continuing to reduce costs in order to deliver the maximum return on assets, companies must find the optimum balance between availability and utilization. Further complicating the process is the need to decrease risks due to regulatory, health and safety, and environmental regulations. Stress wave analysis, as a condition monitoring technique for the quantitative measurement of dynamic contact stresses between moving parts in operating machinery, has increasingly become a preferred choice of many industries in this framework.

SA was originally developed to identify abnormal sources and causes of friction and shock events, and dynamic load transfers in kinematical complex gearboxes, where vibration analysis proved to be impractical. Nowadays, it is utilized a s powerful condition monitoring tool in identifying many defective components such as damaged gears and bearings in pumps, electrical motors, fans, conveyor systems, compressors and turbines. SA systems employ a unique sensor that utilizes the sensor's resonant frequency to selectively amplify low amplitude stress waves, and specialized signal conditioning to filter out structural vibration. This provides the ability to quantitatively measure and trend low energy sources of friction and shock in the presence of high background levels of vibration and audible noise.

The SA technology is indeed registered as a patent of the company SWANtech, which is based in Virginia, U.S.A. It is a company which designs, manufactures, and delivers advanced condition monitoring products that can be used to determine the operational health of critical plant machinery. The company utilizes its SA technology to quantify and track wear and to determine the existence of machine defects and damage. The technology aids in identifying which components are affected by the defect, and provides the opportunity to correct problems prior to the occurrence of secondary damage or catastrophic machine failure. Externally mounted, highly sensitive sensors on a machine's housing detect stress waves transmitted through the machine and convert the data into electrical signals, which are then filtered, measured and analyzed for energy content a real time to identify possible faults. In Europe, the company Evonik Industries AG which is headquartered in Essen, Germany, provides the technology and delivers it to the customers.

j. Thermal Inspection

TI has been practically in use in different industries and for different applications since 1970s. With so many advances being made so rapidly in last 30 years, there has been a jump in production of thermal inspection instruments. Nowadays, different hi-tech TI instruments with specific features can be purchased for reasonable prices. One of the leading companies in producing these tools is the Fluke Corporation and Raytek which is a Fluke company. Fluke Corporation has its headquarters in Everett, WA, U.S. and its European head office is in Eindhoven, the Netherlands. Fluke produces a variety of IR and contact thermometers and thermal imagining instruments which have different maintenance applications.

Different Types of Thermometers

Figure E19 Three different thermometers. From left to right: Fluke 50 Series thermometer: single/dual digital input thermometer with data logging, Fluke 560 Series infrared and contact thermometer, Fluke 570 Series precision infrared thermometer [WS2]

Different Types of Thermal Imaging Instruments

Figure E20 Two different thermal imaging instruments. From left to right: Fluke Ti5x Series thermal imager with thermal sensitivity ≤ 0.05°C for high resolution and high-quality images, Fluke Ti30 thermal imager specially designed for industrial applications [WS2]

Different Applications of Thermal Inspection

Figure E21 Different applications of thermal inspection. From left to right: Electrical - to check electrical panels, wiring and cables, ballasts, transformers, motors and etc.; Mechanical - to check hydraulics, gears, shafts, bearings, pumps and etc.; Facility - to check duct leakage, liquid flow in pipes, roofs, valves, steam traps and etc.; Condition Monitoring and Trending [WS2]

k. Tribological Testing

Nowadays, there are several companies which progressively develop and produce a wide range of tribological testing tools and equipment. Such companies have been named throughout the previous sections. There are even more firms in number that provide oil and wear particle analysis services. These services are relatively inexpensive and some analysis laboratories can provide analysis results within 24 hours. Some services are currently using the internet to provide quick and easy access to the analysis reports. Analysis equipment is also available should a facility wish to establish its own oil analysis laboratory. Unseen corrosion, contaminants, improper lubrication, and machine wear are a primary root cause of equipment failure. Testing machinery lubricants is a necessity but sending samples to an offsite laboratory can sometimes prove to be untimely and inefficient.

Indeed, on-site TT laboratories are becoming more accepted as maintenance professionals realize the profits a well-designed and well-managed lab can generate. The strengths of an on-site lab include rapid sample turnaround and the rich, environment-relevant diagnostics enabled by in-house personnel who are familiar with the site's machines plus the ability to quality control lube oil purchases swiftly. Among all, the ability to react quickly to a potential problem with results in less than an hour compared to 24 or 48 hours for off-site testing is definitely considerable. In general, an on-site oil analysis laboratory is a beneficial addition to any condition monitoring program at any manufacturing or processing plant. However, users must be aware of the failure possibilities and the root causes that may contributed to this, including incorrect instrumentation selection, incorrect test selection, poorly trained personnel, and incorrect or no assimilation with a commercial laboratory. Understanding the pitfalls of embarking on such a project is vital to ensuring its success [413].

I. Ultrasonic Testing

Ultrasound instruments discover early indications of mechanical failure, locate arcing, tracking, and corona in electrical gear and detect all types of leaks. Most ultrasound instruments are lightweight and portable. They translate high frequency sounds produced by operating equipment down to the audible range where they can be heard through headphones and viewed as intensity levels, decibels, on a display panel. Some ultrasound instruments log test information, while others have onboard sound recording along with data logging capability. The ability to view sound levels while simultaneously listening to sound quality enhances the monitoring effectiveness, which permits inspectors to quickly identify changes in equipment that occur from increases in decibel levels or by changes in sound quality. Moreover, ultrasound lets inspectors to discover fault conditions that cannot always be detected by vibration or seen by infrared technology [36].

On the whole, choosing an ultrasound instrument requires taking into account how it will be used. For instance, if sound analysis is important, the instrument should have sound recording capability and be supported by spectral analysis software. For a problem with no data required, a basic analog instrument will satisfy the purposes. If the instrument is to be used to test both airborne emissions such as gas leaks and structure borne (i.e. contact) equipment such as valves, pumps, and motors, frequency tuning can help make subtle sounds more apparent. To provide some examples of different ultrasonic tools used in industry, the following pictures have been selected from the worldwide web.

Analog Ultrasonic Inspection Instruments

Figure E22 Two different analog UT instruments. From left to right: an advance instrument used for contact and airborne applications with frequency tuning and meter mode, a simpler tool for airborne leak detection and mechanical inspection [WS100]

Digital Ultrasonic Inspection Instruments

Figure E23 Two different digital UT instruments. From left to right: a digital instrument used for a variety of applications from leak detection to gearbox inspection, an advance tool which does condition analysis, and data recording and management [WS100]

Digital Ultrasonic Flaw Detectors

Figure E24 Two different types of advance digital ultrasonic flaw detectors [WS88]

Online Continuous Ultrasonic Monitoring

Figure E25 A variety of tools and monitoring applications of online continuous UT. Ultrasonic sensory systems provide information about valve leakage, bearing and lubrication condition, flow disruption, and monitoring of electronic cabinet for arcing [WS100]

m. Vibration Analysis

Vibration signals carry information about exciting forces and the structural path through which they propagate to vibration transducers. A machine or equipment generates vibration of a specific signature when in a healthy condition and the degradation of a part within it may result in a variation in the signature or character of the vibration signals. Therefore, vibration monitoring and analysis is an important means of assessment the condition of a machine. Vibration signals can also be used for fault diagnostics as they change in a variety of ways under different fault conditions.

Several advantages are gained by using the VA. First it is readily supported by the instruments and equipment that is readily available in the marketplace. Second, from an organizational perspective, it has the great advantage that once mastered and practiced it can be used in a broad range of condition monitoring applications. In the last couple of decades there have been terrific technological advancements in design and production of VA related equipment and instruments. One of the companies that produce a wide range of vibration transducers and vibration meters and analyzers is Rion Co., Ltd., which is based in Tokyo, Japan and was founded in 1944.

A Vibration Level Meter

Figure E26 A sophisticated vibration level meter having auto store and timer functions enabling long-term measurement, with frequency analysis unit [WS83]

Pocket Vibration Meters

Figure E27 Three different pocket vibration meters. From left to right: A vibration meter suited for routine maintenance; two compact and lightweight vibration meters designed for quick and easy use in the field [WS83]

Vibration Analyzers

Figure E27 Two different vibration analyzers. From left to right: A handheld FTT vibration analyzer, a portable real-time vibration analyzer [WS83]

n. Visual/Optical Inspection

The visual check and supervision is the quickest way for the first judgment of procedure, specimens and arrangements. If cracks, tears, pores or corrosion scars on the surface are already ascertained in the check with the naked eye and with the aid of mirrors, fiberglass optics or magnifying glasses, the more expensive testing methods can often be cancelled. Recently, there has been a great jump in using of visual/optical inspection as a NDT due to incredible improvements in the related tools and technologies such as borescopes. With advancement of electronic and optic sciences, modern borescopes have features that a decade before they could looking alien. These days, rigid and flexible borescopes with a variety of specifically designed probes can be found in the marketplace, which help obtaining valuable information about the potential failures in difficult-to-reach zones.

Rigid Borescope

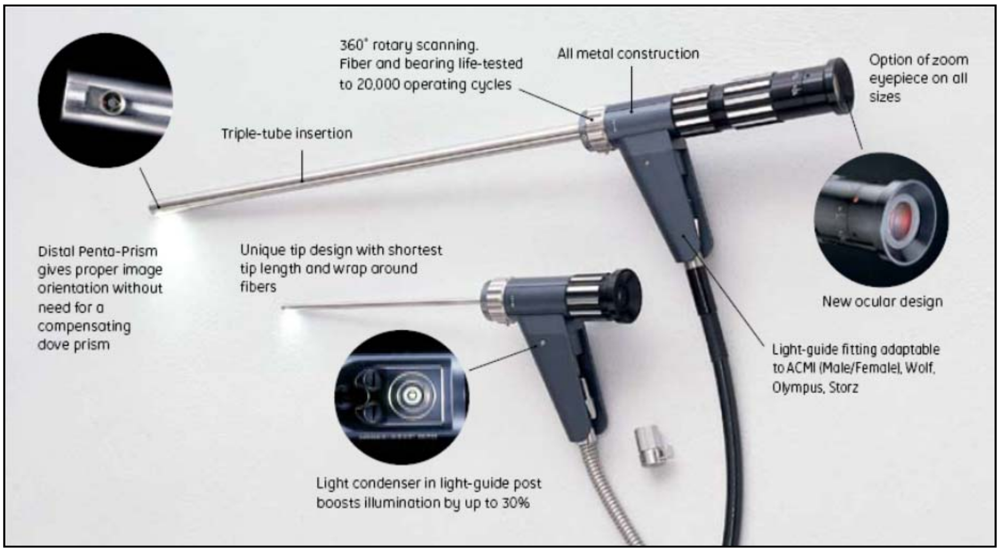
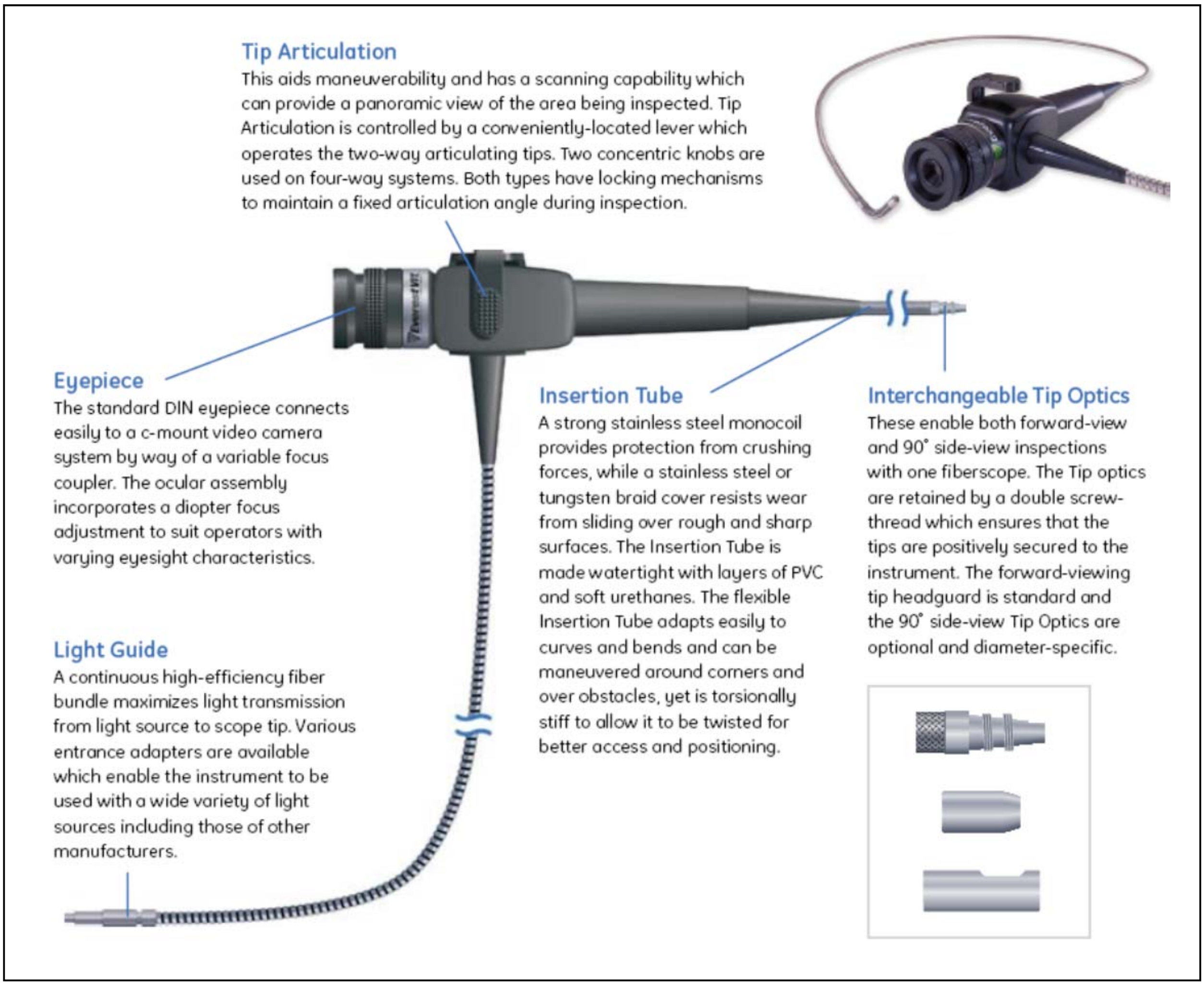


Figure E28 A rigid borescope with brief information of its different components [WS44]

Flexible Borescope



Tip Articulation

This aids maneuverability and has a scanning capability which can provide a panoramic view of the area being inspected. Tip Articulation is controlled by a conveniently-located lever which operates the two-way articulating tips. Two concentric knobs are used on four-way systems. Both types have locking mechanisms to maintain a fixed articulation angle during inspection.

Eyepiece

The standard DIN eyepiece connects easily to a c-mount video camera system by way of a variable focus coupler. The ocular assembly incorporates a diopter focus adjustment to suit operators with varying eyesight characteristics.

Light Guide

A continuous high-efficiency fiber bundle maximizes light transmission from light source to scope tip. Various entrance adapters are available which enable the instrument to be used with a wide variety of light sources including those of other manufacturers.

Insertion Tube

A strong stainless steel monocoil provides protection from crushing forces, while a stainless steel or tungsten braid cover resists wear from sliding over rough and sharp surfaces. The Insertion Tube is made watertight with layers of PVC and soft urethanes. The flexible Insertion Tube adapts easily to curves and bends and can be maneuvered around corners and over obstacles, yet is torsionally stiff to allow it to be twisted for better access and positioning.

Interchangeable Tip Optics

These enable both forward-view and 90° side-view inspections with one fiberscope. The Tip optics are retained by a double screw-thread which ensures that the tips are positively secured to the instrument. The forward-viewing tip headguard is standard and the 90° side-view Tip Optics are optional and diameter-specific.

Figure E29 A flexible borescope with brief information of its different components [WS44]

The choice between rigid and flexible borescopes is dependent on required technological features and also field of application. Rigid borescopes provide higher quality images, are easier to use and are less expensive than flexible scopes of similar quality. It is more feasible to choose a rigid borescope unless the rigidity is a problem. Flexible fiberscope facilitates seeing inside spaces that a rigid borescope cannot penetrate. Nonetheless, there exists video-borescopes to inspect parts faster and more comfortably, attain high-resolution images and record them for documentation; of course, video-borescopes have quite higher prices and are feasible to be used whenever particularly required.

Video-borescope

Figure E30 Two different types of video-borescopes branded as VideoProbe. From left to right: a VideoProbe with a temperature sensor on its probe, a VideoProbe with high portability and very high screen resolution [WS44]