Preventive Arms Control for Small and Very Small Armed Aircraft and Missiles

Report No. 2

Survey of the Status of Small and Very Small Missiles

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Contents

Abbreviations and Acronyms

AIAA	American Institute of Aeronautics and Astronautics
APKWS	Advanced Precision Kill Weapon System
DoD	Department of Defense
DSF	Deutsche Stiftung Friedensforschung (German Foundation for Peace Research)
HE	High explosive
HEAT	High explosive anti tank
LAW	Light Anti-tank Weapon
MANPADS	Man-portable air defence systems
MHTK	Miniature Hit-To-Kill
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command
NAWCWD	Naval Air Warfare Center, Weapons Division
n.d.	no date
PzF	Panzerfaust
R&D	Research and development
RF	Radio frequency
RPG	Rocket-propelled grenade
TU	Technische Universität
UAV	Uninhabited aerial vehicle
UK	United Kingdom
UMS	Unmanned/uninhabited System
US(A)	United States (of America)

1 Introduction

The project 'Preventive Arms Control for Small and Very Small Armed Aircraft and Missiles', funded by the German Foundation for Peace Research DSF, is investigating the properties to be expected of ever smaller aircraft and missiles, including their use in swarms (https://url.tu-dortmund.de/pacsam). Small and very small aircraft are treated in the report no. 1 from the project (Pilch et al., 2021a). This report no. 2 covers small and very small missiles, virtually all of which are armed.[1] Further reports will consider dangers and preventive arms control.

The focus is on missiles with rocket propulsion and the traditional rocket shape. Cruise missiles, usually counted as missiles, technically rather are uninhabited aircraft and are excluded here.[2] Military rockets have been used since centuries; in World War II artillery rockets were famously used by the Soviet Union, and Nazi Germany introduced the first long-range rocket with the V2 missile. Later, many types of rocket-propelled guided missiles were introduced, launched at the surface or in the air, against surface or air targets. These missiles have lengths of several metres and diameters of several times 0.1 metre. Smaller types were introduced – some already in World War II – to be carried and launched by a person, mainly against tanks (bazooka) or aircraft (man-portable air defence system, MANPADS). Most of these have diameters above 69 or 70 mm, and their types and properties are known well. In order to focus on new developments, we exclude them by our definition of small missiles (see Chapter 2), but some existing types are below and thus are included in the database.

The principal possibility of much smaller missiles was mentioned early, fuelled by emerging microsystems technology and nanotechnology, but proposals for limits or prohibitions[3] have not been taken up so far. Only in recent years have projects for small and very small missiles come up (for the definitions see Chapter 2). With the growth in small, armed uninhabited aerial vehicles (UAVs, described in Pilch et al., 2021a) increasing military interest in small missiles carried by the former is expected.

To assess the potential effects to be expected from small and very small missiles, including dangers to military stability and international security, as well as options for preventive arms control, the first precondition is reliable information about already existing systems and current trends in research and development. Based on databases, scientific and internet publications, this report lists small and very small missiles deployed and used worldwide, as well as systems under research and development. As far as has been available, their basic properties with the year of introduction are listed to allow statements

1 There are only very few civilian or military unarmed uses of small missiles or rockets. Beside fireworks and hobby, small rockets are used for weather, sounding, signalling, as decoys or for shooting a lifeline to a stranded ship (Sutton & Biblarz, 2001: 25).

2 Note that sometimes loitering munitions, that is propeller-driven small aircraft with many minutes endurance, are called 'loitering missiles' (Aerovironment, 2021a, b); we count them as UAVs and include them in our corresponding Report no. 1 (Pilch et al., 2021a).

3 Mainly by (Altmann, 2001; Altmann, 2006): prohibition of missiles and 'mobile micro-robots' below 0.2-0.5 m size.

on trends of missile capabilities in recent years. Non-armed systems and systems for civilian purposes are not included.

In order to minimise a contribution to proliferation of these systems, only public sources were investigated, mainly the internet. Furthermore, where information is incomplete, no estimates based on the laws of physics or stemming from engineering expertise are given. Different from the situation with small or very small armed UAVs, improvised or modified versions of small or very small missiles have not become known yet.[4]

There are a few catalogues listing missiles; probably the most authoritative are the ones from Jane's, they cover many more weapon and ammunition types (Dhingra, 2019; Udoshi, 2019; Widlund et al., 2019). Missile arsenals from various countries are given by the Center for Strategic and International Studies (via CSIS, 2021). Chinese missiles are listed in e.g. (GlobalSecurity, 2021a). Designations and properties of US military missiles and rockets, including historic ones, are contained in an inofficial directory (Parsch, 2009). The English Wikipedia has several lists that in most cases contain links to individual articles (Wikipedia ASM, 2021; Wikipedia LMI, 2021; Wikipedia MAN, 2021; Wikipedia ROC, 2021; Wikipedia SHO, 2021).

Different from small UAVs, where a significant amount of research is being published (see Pilch et al., 2021a), scientific literature on small missiles is scarce. Some texts treat solid-rocket propulsion in detail, e.g. (Zecevic et al., 2011). General aspects of missile aerodynamics and design are treated in textbooks such as (Nielsen, 1960; Jensen & Netzer, 1996; Sutton & Biblarz, 2001; Fleeman, 2006; Wolff, 2006).

The report is structured as follows: Chapter 2 explains the general understanding of the term 'missile' and presents our definition. Also explained are our notions of a 'small missile' and a 'very small missile'. Classes and typical properties of missiles are described in Chapter 3. Chapter 4 presents general physics of rocket propulsion and of aerodynamics. Chapter 5 gives a technical overview from the body and launch via the motor and guidance to the effects on targets. Two examples of small missiles are shown in Chapter 6. Chapter 7 covers military aspects, and Chapter 8 presents summary properties of the database which itself is presented in the appendix A and at an internet location.[5]

4 With the exception of the first version of the Hamas-produced Qassam rockets. Qassam-1 had a diameter of 60 mm while the later versions had/have 150 and 170 mm (GlobalSecurity, 2021b). Outdated systems are excluded from our considerations. The Wikipedia entries of 115 mm for Qassam-1 to Qassam-4 are wrong probably (Wikipedia QAS, 2021).

5 https://url.tu-dortmund.de/pacsam for the project description and https://url.tu-dortmund.de/pacsam-db for a description of the databases. The small and very small missile database is available at https://url.tu-dortmund.de/pacsam-db-sm.

2 Definitions

2.1 Missiles

There are several understandings of what a missile is. On the level of general parlance, the Merriam-Webster Dictionary states: ‘an object (such as a weapon) thrown or projected usually so as to strike something at a distance’ and mentions ‘stones, artillery shells, bullets, and rockets’ as examples (Merriam-Webster, 2021). The Encyclopedia Britannica (2021) is more specific, concentrating on the weapon function: ‘Missile, a rocket-propelled weapon designed to deliver an explosive warhead with great accuracy at high speed.’ (Encyclopedia Britannica, 2021). Among the military glossaries, the ‘Dictionary of Military and Associated Terms’ of the US Department of Defense (DoD) has no entry for ‘missile’, only combinations ‘ballistic missile’, ‘cruise missile’ and ‘guided missile’ that connect the word ‘missile’ with special properties (US DoD, 2021). The ‘NATO Glossary of Terms and Definitions’ defines a missile as: ‘A self-propelled munition whose trajectory or course is controlled while in flight’ (NATO, 2020). This is used implicitly in various combined terms, such as ‘air-to-surface missile’ or ‘ballistic missile’ (‘guided missile’ and ‘cruise missile’ do not occur, and ‘munition’ is not defined either). Different from the US DoD Dictionary, the NATO Glossary also contains definitions for ‘rocket’: ‘A self-propelled vehicle whose trajectory can possibly be controlled in the final phase of its trajectory, but neither during the initial phase, nor during the ballistic trajectory.’ and for ‘projectile’: ‘An object capable of being propelled by a force normally from a gun and that follows its trajectory by virtue of its kinetic energy.’

Following the NATO definitions, the difference between a missile and a rocket is that the trajectory of the former is controlled while the one of the latter is not controlled at least for the initial and ballistic phases, in many cases over the full trajectory. Self-propulsion needs to be present in both; if something is thrown from a gun, it rather counts as a projectile. We do not follow the NATO understanding in that we count systems without trajectory control as missiles, too.

Here a conceptual problem exists with cruise missiles. Traditionally, they are counted as missiles. But technically they are rather uninhabited aircraft, having the shape of the latter, with two extended wings, a horizontal and a vertical stabiliser, and an airbreathing engine burning liquid fuel, usually running over the whole flight time.[6,7] Other ‘normal’ missiles have only small wings, often symmetrical in four angles around a body with circular cross section (see Figure 3.1 below), so that no standard horizontal flight attitude (around the

6 Probably it is mostly for non-technical reasons that the US Department of Defense has excluded cruise missiles explicitly from its definition of ‘Unmanned Vehicles’ (US DoD, 2007: 1).

7 Fabian Hoffmann has discussed the definition problem and has proposed ‘to define cruise missiles as *airborne vehicles continuously propelled by airbreathing engines, following a non-ballistic and relatively direct flight path, and engaging their targets at stand-off range*.’ (Hoffmann, 2021, emphasis in original).

body axis, the roll axis) exists, and they use rocket propulsion, working only over a part of the flight path.

For the purposes for our project and this report, we use a narrower definition of a missile, being aware that there are hybrid forms and grey areas. For example, a missile body may have an elliptical, not a circular cross section; one pair of wings may be wider or longer than the other, creating a preferential horizontal attitude; an air-breathing instead of a rocket engine may be used (e.g. of ramjet or scramjet type); rocket propulsion may be combined with air breathing.

Definition 2.1: Missile (in the present context)

A vehicle, in military use usually carrying or acting as a weapon, travelling above the surface of the Earth (through air or outer space), usually at a speed above the speed of sound, usually with a body of circular cross section, usually with wings, fins etc. arranged symmetrically at more than two angles around the body axis, usually propelled by a rocket engine, in most cases with attitude and trajectory control.

Thus here unguided rockets count as missiles, too. Projectiles shot out of a barrel by the pressure of the propellant gases therein do not count,[8] but if they have an additional rocket engine, they do.

The definition is somewhat vague in order to provide leeway in the spectrum from the ‘usual’ cases to modified forms, where e.g. two wings are somewhat bigger than the two others, providing a preferential attitude, or where an air-breathing engine is used.

2.2 Small and Very Small Missiles

There is no standard definition of a ‘small’ or a ‘very small’ missile. We use the body diameter for this purpose, excluding wings, fins and control flaps, and independent of length. In case of a non-circular cross section we use the largest diameter. If the missile diameter varies along the missile length, we use the biggest value.

Many existing missiles have diameters of 200 mm and above, these are clearly outside of our topic. To focus on new developments and not flood the list with traditional missiles of MANPADS, most having diameters of 69 to 72 mm,[9] and rockets of hand-held anti-tank

8 Note that some launchers of projectiles compensate for the recoil by ejecting material (often part of the pressurised burn gases) at the back. Such recoilless launchers are sometimes called rocket-propelled grenades, even if rocket propulsion is not involved (Newhouse, 2011).

9 The section ‘Man-portable surface-to-air missile Systems’ in (Widlund et al., 2019: 668-721) gives 41 missile/system types from 17 countries (and one ‘International’ one); 31 have 70-72 mm diameter. The other ten types have: 76, 80, 93, 106 and 127 mm. Note that upgrades or modifications from earlier licence production often, but not always, count as new types. Important families include the Chinese QW, the Russian Igla and Strela and the US Stinger systems. The US Stinger is sometimes listed with 70 mm (Wikipedia FIM-92, 2021; Military Today FIM-92, n.d.) while Jane’s catalogues give 69 mm as the body diameter (Udoshi, 2019: 63-65; Widlund et al., 2019: 715-721 - here with an obvious typo ‘690 mm’). Such differences

weapons (‘bazookas’), many of which have diameters above 80 mm,[10] in the present context a *small missile* is one with a diameter below 69 mm. This also excludes the unguided US missile Hydra-70 (70 mm) (e.g. General Dynamics, 2020) and the converted version (guidance section inserted between the rocket motor and the warhead), the Advanced Precision Kill Weapon System (APKWS) (e.g. NAVAIR, n.d.); both have been used and exported in extremely high numbers. We denote a missile as *very small* if its diameter is equal to or below 40 mm. Both limits are somewhat arbitrary, and properties do not change abruptly as they are crossed.

Table 2.1: Definitions of ‘small’ and ‘very small’ sizes of missiles.

Defining property	‘Small’	‘Very small‘
Biggest body diameter	< 69 mm and > 40 mm	≤ 40 mm

It has to be noted that some historical anti-tank missiles had biggest diameters below 69 mm, e.g. the first versions of the Bazooka of the US Army with 66 mm (produced in World War II, later models had 89 mm) (Rottmann, 2021), or the Leichte Panzerfaust of the German Bundeswehr, in use until 1992, that had a 44 mm barrel and a 67 mm warhead (Wikipedia PZF, 2021). Such systems are excluded from the database. But there are also very few types below 69 mm that are in use; examples are the US M72 Light Anti-Tank Weapon (66 mm, one version 42 mm) (Cooke, 2008; NAMMO, 2018; Wikipedia M72, 2021), the Russian RPG-18 (Military Today RPG, n.d.; Wikipedia RPG-18, 2021) or the Polish RPG-76 Komar (68 mm) (Wikipedia KOM, 2012). They are included in the database, also in order to have a few existing systems for comparison with the new ones.

There is a type of rocket-propelled grenades that are launched from a 40-mm tube launcher, often an RPG-7.[11] While the missile parts in the tube have 40 mm diameter, in most cases the warhead protrudes from the launch tube; diameters to 120 mm occur. Dhingra (2019: 305-324) lists dozens of types with 69 mm or above, around 15 between 40 and 69 mm, and fewer than 10 with 40 mm or below. The latter two categories are included in the database.

may have to do with the tube being a bit wider, or with rounding from 2.75 inch = 69.85 mm.

10 Some anti-tank missiles have thinner bodies than 69 mm but a thicker warhead, e.g. the Panzerfaust 3 of the German Bundeswehr has a 60 mm barrel, but a 110 mm warhead (Streitkräftebasis, 2004; Wikipedia PAN, 2021).

11 Developed in the Soviet Union and widely exported (Wikipedia RPG-7, 2021).

3 Classes and Typical Properties of Missiles[12]

Missiles are divided in classes by different properties. With respect to range, one can use the categories of the nuclear arms-control treaties: long-range missiles can cover more than 5,500 km, intermediate-range ones were defined in the INF Treaty as having ranges between 500 and 5,500 km, short-range missiles are below 500 km or sometimes below 1,000 km. All these are called ballistic missiles since after burnout they follow a ballistic trajectory, in part outside of the atmosphere, there they are only influenced by the gravity force.

Tactical missiles for battlefield use have ranges from a few hundreds of metres to dozens of km or, in some cases, a few hundreds of km. They do not leave the atmosphere. Early versions followed ballistic trajectories (i.e., a parabola modified by air-drag deceleration, flat over 100 m, steep over dozens of km) after burnout, e.g. artillery rockets. Their attitude is stabilised by spin (as with projectiles shot from a barrel with rifling) and/or by (slightly angled) fins at the back. Guidance started in World War II, but was expanded to most missiles in the decades thereafter.

Guided missiles can be classified by the general location of the shooter and of the target, e.g. surface to air. Another categorisation goes by the target type, e.g. anti-tank or anti-ship.

Missiles can carry different types of warheads. Nuclear warheads of mass 100 kg and more require correspondingly big and heavy missiles. Chemical and in particular biological weapons could have lower masses, depending on the size of the intended target area. To be used against one or a few persons, a small or even very small missile (in the sense used here) could carry them. However, such weapons are prohibited by the corresponding conventions. Most warheads of tactical missiles use conventional high explosive (HE) for overpressure damage, sometimes augmented by fragments, with masses of several kg to tens and hundreds of kg, depending on the intended damage radius. Against armour and structures, a high-explosive anti-tank (HEAT) warhead uses a shaped charge where a jet is formed that focusses the explosive energy and penetrates the material; their masses are on the order of kg. Other destruction modes are by submunitions or kinetic-energy penetrators. There are also versions of missiles that provide illumination or that release flares to confuse infrared sensors or chaff, small metal-foil strips to confuse radars .

Intermediate- and long-range missiles consist of several stages; higher burnout velocities can be achieved if the empty lower stages are separated and only the remaining ones are accelerated further. Short-range and tactical missiles have one stage; to prevent injury from the rocket exhaust, some shoulder-launched missiles use a small thrust for ejection from the tube and start the main thrust at several 10 metres distance. In general the time course of thrust over the burn time can be controlled by a specific design of the solid-fuel grain and its geometry, including the cavities acting as burn chambers.

By type of propulsion one distinguishes liquid- and solid-fuel missiles. Liquid fuel can provide higher exhaust velocities, but brings particular problems, in particular with storage. For practical reasons virtually all military missiles (with rocket propulsion) use solid fuel.

12 Nielsen, 1960; Jensen & Netzer, 1996; Fleeman, 2006; Sutton & Biblarz, 2001; Wolff, 2006.

The size and mass of a missile follow from its mission. Basic parameters are the mass and size of its payload, the range over which it is to be carried and the required speed, together with the altitude profile and the amount of manoeuvering that are expected.

The rocket engine accelerates the missile to high, in most cases supersonic, speed. After burnout the flight can continue for a considerable time and distance, slowly decelerating due to air drag while still being able to manoeuver.

Most missiles fly fast enough that their weight can be compensated mainly by the lift force arising at the missile body; extended wings as in winged aircraft are not needed. To produce additional lift, to stabilise the attitude and to control the trajectory, canards, wings and tail fins can be added to the body (Figure 3.1). As long as a guided missile moves in the air, the trajectory can be controlled by changing the angle of such surfaces or of additional control flaps. Such flaps, often near the back end, can be used to produce a moment and turn the missile in a different direction horizontally and vertically, in particular to maintain an intended angle of attack and course. Modifying the exhaust flow while the engine is still burning, or igniting small lateral thrusters, are other methods of attitude and trajectory control (that would work outside of the atmosphere, too).

Reacting to wind and other external influences as well as to approach a possibly mobile target may need control of the missile movement on very short time scales.

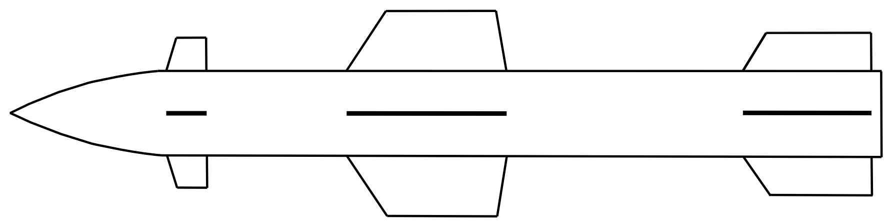


Figure 3.1: Possible positions of lift, stabilisation and control surfaces: canards (front), wings (near centre of gravity), tail.

4 Physics of Rocket Propulsion and Aerodynamics

This chapter gives an elementary introduction into rocket propulsion and aerodynamics of missiles; for in-depth introductions see (Nielsen, 1960), (Jensen & Netzer, 199), (Sutton & Biblarz, 2001), (Fleeman, 2006) and (Wolff, 2006). Non-technical readers may skip it.

4.1 Rocket Propulsion

A rocket burns fuel to produce high-pressure gas; different from an engine that takes in air from the surrounding atmosphere to burn the fuel carried in a tank, the oxidiser has to be provided by the propellant(s). Burning means chemical reaction, either by rearrangement of the atoms in the monopropellant molecules or by reaction between fuel and oxidiser molecules. In liquid-fuel rockets, the two are pumped from separate tanks and mixed in a burn chamber, in solid fuel both components are mixed at the production stage. Burning creates hot gases under high pressure.

The gases flow through a nozzle at the back at high speed which produces the forward thrust by the action-reaction law. The propelling force F , that is the rate of momentum transfer to the rocket body, is the product of the mass-exhaust rate $\dot{m}=dm/dt$ (the time derivative of the momentary rocket mass m) times the exhaust speed v_e , both are about constant in many cases:

$$F=\dot{m}v_e \ . \qquad (4.1)$$

Because the rocket mass $m(t)$ decreases as burnt fuel is expelled, for constant force the acceleration a increases with time:

$$a(t)=F/m(t) \ . \qquad (4.2)$$

Assuming constant burn rate and absent other forces such as gravity or air drag, the velocity of the rocket at burnout v_B is given by the rocket equation:

$$v_B=v_e\ln\left(\frac{m_0}{m_B}\right) \qquad (4.3)$$

where m_0 is the mass at the start of the burn and m_B is the mass at its end. In case of more than one rocket stage, the respective masses and exhaust speeds have to be used, and the final velocity is the sum of the individual velocity increments.

Depending on the direction of flight, a component of the gravity force acts against the thrust force, leading to a lower real velocity. As long as the rocket is in the air, the drag force acts against the thrust force, also reducing the velocity. Since the drag increases with the square of the velocity, for constant thrust and air density (at constant altitude), at some point the drag will balance the thrust and the speed will not increase further.

The burnout time of missiles often is much shorter than the total flight time. Thus the engine thrust accelerates the missile and puts it on the intended trajectory after which it continues due to its inertia, influenced by the gravity force and the aerodynamic forces. As long as the missile is moving in the atmosphere its attitude and trajectory can be controlled by varying the angle of fins or flaps, while the engine is still burning also by influencing the exhaust direction. Missiles flying through outer space usually have no thrusters, so they fall along a gravity ellipse in that phase – but this is not relevant for small missiles that do not leave the atmosphere.

4.2 Aerodynamics

If some body moves through air with a velocity v_0 – or, equivalently, if air flows in the opposite direction toward the body – the body experiences a force, the integral of the pressure field over the surface. It can be treated as a single force acting on the centre of pressure. Figure 4.1 shows the situation for a missile moving in a vertical plane, that is without horizontal movement. The force component orthogonal to the velocity direction is called lift *L*, it is the sum of the lift from the body and from wings, fins etc., with the body producing the highest share usually. Extended lateral wings as in aircraft are not needed because the missile velocity is much higher. The force component in the velocity direction (but opposite to it) is called drag *D*. The integrated weight force *W* can be treated as acting on the centre of gravity CG. *L* and *D* depend on the angle of attack *α* between the body axis and the velocity.

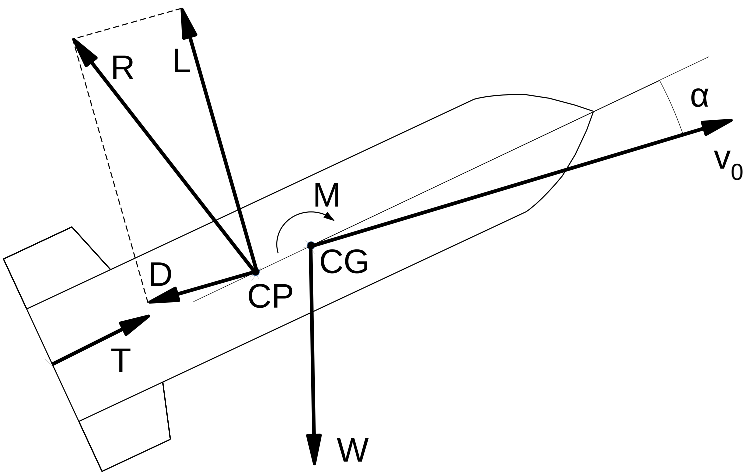


Figure 4.1: Forces and moments acting on a missile climbing in a vertical plane, in a sideways view. The centre of gravity CG, where the weight force ***W*** acts, moves through the air with a velocity vector $\boldsymbol{v}_0$. The body axis is at an angle of attack *α* from the velocity direction. The resulting aerodynamic force ***R*** has a component orthogonal to the velocity, the lift force ***L***. The other component is the drag force ***D*** acting opposite to the velocity. Lift and drag forces can be treated as acting on the centre of pressure CP. During powered flight there is also the thrust force ***T*** for overcoming the drag, providing acceleration, compensating the weight and, in climb, increasing the altitude. A moment ***M*** around the centre of gravity arises if the centre of pressure does not coincide with the former. Another moment arises if the thrust vector does not lie in the body axis.

If the centre of pressure CP does not coincide with the centre of gravity CG, a moment about the latter arises, equal to the vector product of the vector between the two centres and the total aerodynamic force vector. If the centre of pressure lies behind the centre of gravity, the moment tends to reduce the angle of attack, the missile is statically stable. In the opposite case the moment increases the angle of attack; statically instable missiles need to be controlled actively to prevent tumbling. Similar considerations apply to yaw angle and sideslip if a horizontal curve is flown.

Lift and drag scale linearly with the cross-section area S of the body and the so-called dynamic pressure, which is one half of the air density times the square of the velocity:

$$L = \frac{\rho}{2} v_0^2 S C_L \ , \quad (4.4)$$

$$D = \frac{\rho}{2} v_0^2 S C_D \ . \quad (4.5)$$

Here ρ is the air density and C_L and C_D are the lift and drag coefficients, respectively. For small angle of attack α, C_L depends linearly on α with symmetry around zero for a usual missile; C_D varies quadratically with a minimum at zero.

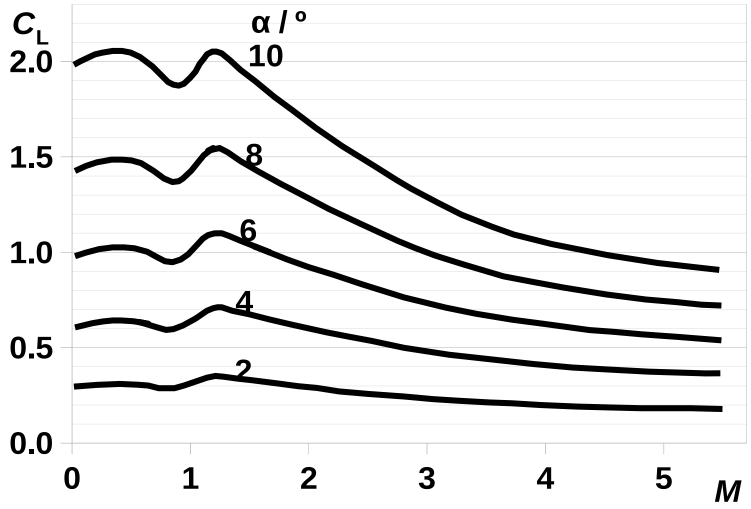
Lift-to-drag ratios of missiles with circular cross sections are in the range of 2 to 5 (Fleeman, 2006: 2.5).

The lift and drag coeffients change if the velocity approaches and transcends the speed of sound a (in dry air 343 m/s at 20 °C, 299 m/s at -50 °C (e.g. in 10 km altitude). The relative speed is described by the Mach number

$$M = \frac{v_0}{a} \ . \quad (4.6)$$

As an example, Figure 4.2 shows the dependence of the lift and drag coefficients on Mach number for various angles of attack for the Nazi-German V2 missile (with jet off, without exhaust-plume effects). Higher angles of attack than 10° do occur, but above about 20° the flow separates from the vehicle, it stalls with much reduced lift.

While the lift coefficient rises somewhat around M = 1, the drag coefficient shows a drastic increase, due to the production of the Mach-cone waves at and above the speed of sound.



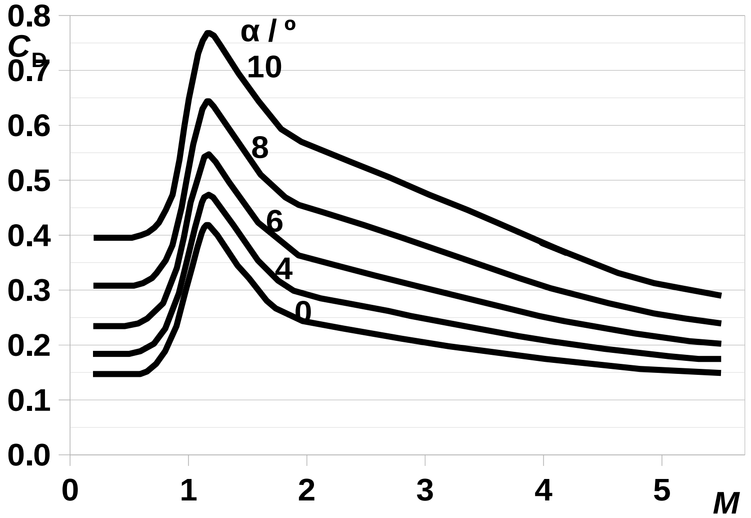


Figure 4.2: Dependence of lift coefficient C_L (top) and drag coefficient C_D (bottom) on Mach number *M* for various angles of attack *α* of the V2 missile (jet off, no exhaust-plume effects (after Sutton & Biblarz, 2001: Fig. 4.3). (The lift is zero for zero angle of attack.)[13]

13 This can be different in winged aircraft in case of camber (asymmetric top and bottom curves).

5 Technical Overview[14]

Different from the situation with small and very small uninhabited aircraft (Pilch et al., 2021a), there are only very few new types of small and very small missiles in existence or in development, and apparently not much public research is being done on them. Thus there is a dearth of information, there is not much established technology and practice, and the following considerations necessarily remain on a relatively general level, based on existing missiles most of which are not small.

The design of missiles has many parameters that can be controlled; each type is optimised in a complex, iterative process depending on the intended military mission and its conditions, within the given technological possibilities.

A (guided) missile with solid fuel consists of the following components:

- Body and surfaces,
- Launch system,
- Motor with casing, propellant and nozzle,
- Flight control system,
- Navigation, guidance and targeting system,
- Warhead.

These are covered in the following sections.

Body and surfaces

The body provides the mechanical stability, it has to withstand the various forces, pressures and (bending) moments as well as vibration and heating, stemming from the movement through the air, from the engine thrust and from the control flaps. The body diameter is a decisive parameter for air drag, also the nose fineness. Materials are metals or fiber-reinforced composites. The geometry and size of canard, wing, tail and control surfaces vary widely.

Launch system

In case of vertical launch the weight force points just backward so that it is compensated for by the engine thrust. More often missiles are launched horizontally or in a slant upward direction, so that the weight force tends to turn the missile downward. If a missile starts non-vertically at zero speed, during the very first part of the trajectory there needs to be some mechanical guide in the form of a rail or tube, at least for the missile length. This mechanism is used in most shoulder-launched missiles. If the burn time is not extremely short and acceleration continues after the missile leaves this guide, it still has a low velocity. To bear its weight by aerodynamic lift, a higher angle of attack is needed. As the velocity increases the angle of attack can be reduced. In case of a launch from a moving aircraft, on the other hand, the missile has a considerable velocity from the start.

14 Nielsen, 1960; Jensen & Netzer, 1996; Fleeman, 2006; Sutton & Biblarz, 2001; Wolff, 2006.

Motor

In a solid-fuel missile the motor case contains the propellant grain and has to withstand the high pressure from the burn gases and their heat. Often it consists of filament-reinforced material and is part of the primary structure. The propellant grain may have varying composition, the shape of the cavity acting as burn chamber determines the time course of the burn rate and thus the thrust. They are about constant with end burn, increases linearly over time with cylindrical burn and can be kept about constant – at a higher rate of burn – with a star-shaped cavity. Some motors reduce the thrust after the initial acceleration to sustain the speed for a longer time and keep the needed manoeuvrability.

The high pressure drives the burn gases through the nozzle that forms the supersonic exhaust jet; the nozzle has to withstand the heat and erosion for the burn time, often by ablative material.

To reduce the backward damage area from the exhaust gases, some shoulder-fired missiles use low thrust at first, starting the main burn only after covering several ten metres.

The burn times vary – for anti-tank missiles from fractions of a second to a few seconds, for air-launched missiles several seconds, possibly with a sustain phase of tens of seconds.

Because the air drag increases with the square of the velocity, for constant thrust and constant altitude at some point a balance with the drag would be reached and the speed would no longer increase.

Flight control system

The motion of a guided missile is steered by varying the relative angles of control fins – as long as it is in the atmosphere – or the direction of the thrust – as long as the engine is working. In this way the trajectory toward the general region of a target and the final approach can be controlled, following a program and reacting to external disturbance, e.g. from wind. To maintain the intended angle of attack – that is e.g. decreased as the missile gains speed and needs less lift – and to follow the planned trajectory, continuous corrections on short time scales are needed. Guided missiles can fly horizontally and can change altitude as the mission profile demands. Some dive down in the final phase, hitting the target from above.

During burn the missile accelerates for a short time, after burnout it decelerates slowly from air drag, according to the momentary conditions of air pressure (that decreases with altitude), angle of attack and speed. The manoeuvrability decreases in parallel since the lift that is used for (horizontal or vertical) turns depends on the square of the speed.

Whereas the energy for propulsion stems from the rocket fuel, the flight control system needs some additional power for sensors, processing electronics, control-fin movement, warhead arming/ignition etc.

Very simple unguided missiles, on the other hand, follow a ballistic trajectory (after burnout, a parabola modified by air drag if they stay in the atmosphere); the attitude is oriented in the momentary direction of flight by static stability, usually combined with rotation about the body axis, similarly as with projectiles shot from a rifled barrel. Without guidance much higher miss distances occur.

Navigation, Guidance and Targeting

Usually missiles are launched in the general direction of the target, but turning after launch is possible; in particular vertical launch is often used. Due to short flight times, missiles have to move more or less directly to the target, longer detours or loitering for target search are excluded. If unguided with a target at close range, the shooter can set the precise direction with the help of a sight. If guided, several methods can be used. In remote control, command signals can be sent by (unreeling) wire or radio. In beam riding a (radio, radar, laser) beam is directed toward the target and the missile controls its trajectory to stay in the beam. Automatic control can track the target as well as the missile and guide the latter to a collision. Homing missiles use some signal from the target to approach it – actively illuminated by an external radar or laser, or passively relying on infrared emissions or a video image. Some have their own radar seeker. Navigation in the first flight phases can use inertial systems or navigation satellites; if the target co-ordinates are fixed and known accurately enough, these may suffice.

Of course, active systems come with power and weight penalties which make their use on small missiles difficult.

Fusing

Explosive warheads need to be initiated. This can be done by contact when the target is physically impacted. Alternatively, a firing signal can be sent when some ambient condition or sufficient proximity to the target is sensed or when a pre-determined time has elapsed. Usually a primary explosive is used to initiate the main charge.

The fusing system also provides safing and arming of the weapon.

Damage Mechanisms

Small and very small missiles equipped ith or acting as conventionally weapons can use blast overpressure from an explosion, possibly enhanded by explosive overpressure. Against non-armoured or lightly armoured targets, metal fragments or darts can increase the effect and the damage area. A direct mechanical hit by the missile is possible, but requires high accuracy. For penetrating armour, a shaped charge is needed. For more detail see Chapter 7. Since the destructive effect or the affected area increases with the warhead mass, for given missile size and mass there is a trade-off with the amount of fuel carried and thus the range.

Principally, small and very small missiles could carry and apply chemical and biological weapons, prohibited by the respective conventions of 1993 and 1972, respectively. When chemical weapons were still in storage, grenades contained kilograms and bombs dozens of kilograms of agent for area and mass effects (Wöhrle, 2017: Fig. 3-27, 213f). Thus a small missile could act against one or a few persons only. Biological agents can be more effective per mass by orders of magnitude (Nixdorff, 2017: Tab. 4-3) so that a small missile could affect many more people by infection over time.

6 Examples

Here two examples of small missiles and one very small one are shown – the first a traditional system, the second and third very small ones. For dimensions, weights and propulsion types of selected existing US missiles, none of which are small in the present sense, see (Sutton/Biblarz, 2001: Table 1-6).[15]

M72[16]

The portable anti-tank rocket launcher M72 LAW (Light Anti-Tank Weapon) has been deployed by the US Army since 1963, with several improved versions since then. Many armed forces use it. At present it is produced by NAMMO. The missile length is 0.508 m, the diameter 66 mm (Figure 6.1).

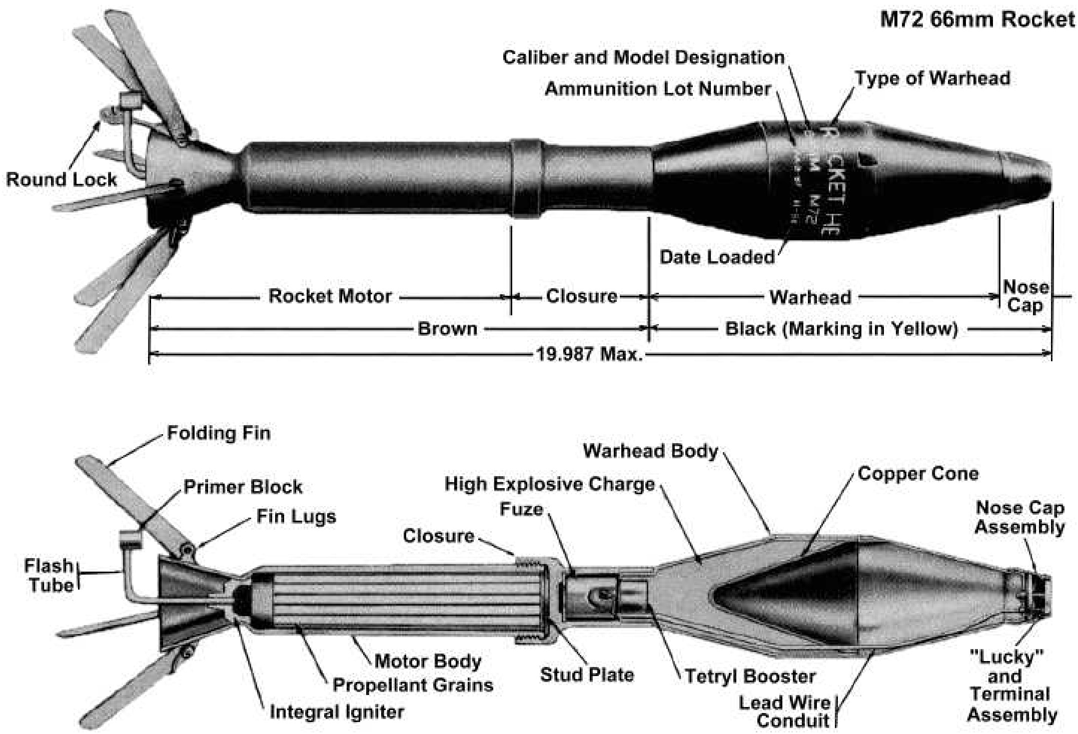


Figure 6.1: Missile of the anti-tank rocket launcher M72 (USA, in use in many countries) (public domain). Diameter 66 mm, length 0.508 m, mass 1.8 kg. For very fast burn the propellant is arranged as an array of tubular sticks. The warhead contains the conical shaped charge (Wikimedia M72, 2021).

15 The smallest in the list is the Redeye surface-to-air missile with 73 mm diameter, 1.2 m length and 8 kg mass. The next are Chaparral (surface-to-air) and Sidewinder (air-to-air) (both 128 mm) and then Hellfire and TOW (both anti-tank, 177 mm). All these have one solid-fuel stage.

16 US Department of the Army, 2001; Cooke, 2008; Nammo, 2018; Wikipedia M72, 2021.

With a muzzle velocity of 145-200 m/s (clearly below the speed of sound) the effective firing range is 200-350 m, the maximum range is 1.0-1.2 km.[17] The HEAT shaped charge is ignited by a piezo fuse and can penetrate 300 mm of steel. The rocket burns out while it is still in the launch tube, in 5-10 ms, due to an array of multiple tubular propellant sticks.[18] Assuming an average speed of 180 m/s, a target in 350 m would be reached in 2 s.

NAVAIR Spike[19]

The Weapons Division of the US Naval Air Warfare Center (Naval Air Systems Command, NAVAIR) is developing a small missile, the Spike, which weighs much less and is much less expensive than existing guided missiles (cost goal is $5,000) (Figure 6.2).

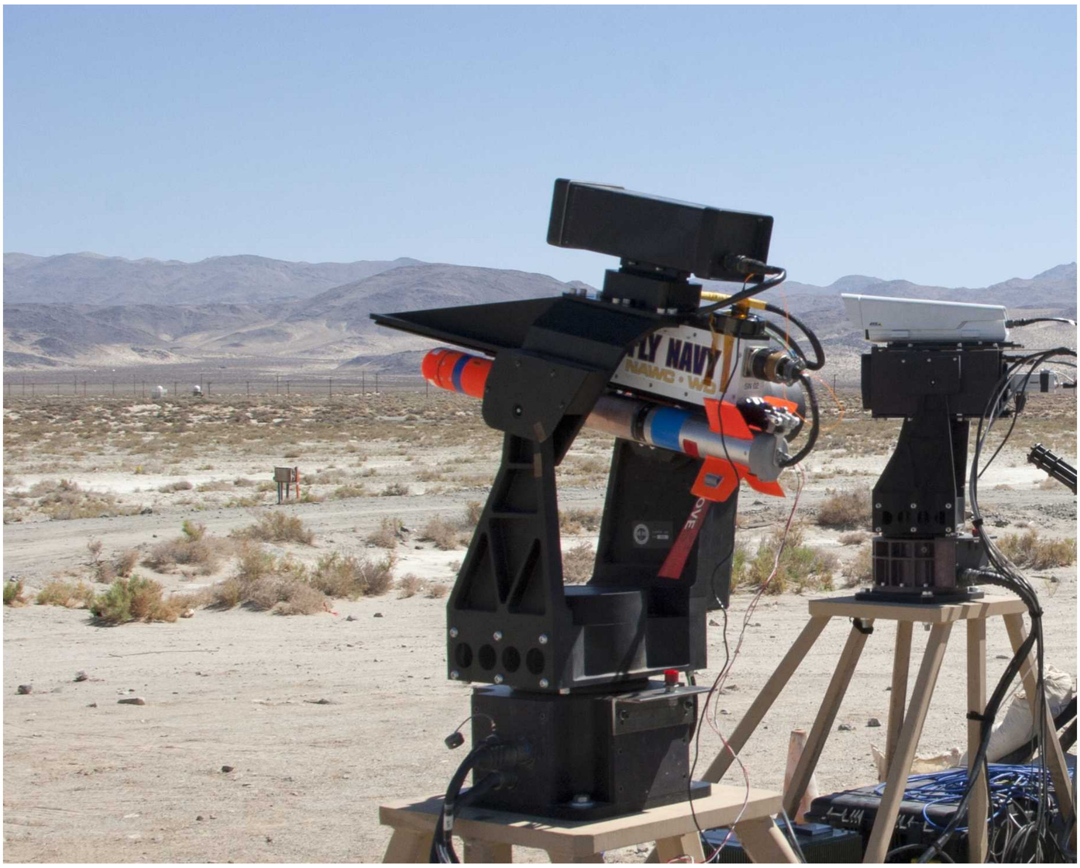


Figure 6.2: Developmental missile NAVAIR Spike on a launch rail. Later versions use folding wings for tube launch (public domain). Diameter 57 mm, length 0.635 m, mass 2.8 kg (NAVAIR, 2014a).

17 For the version M72A9 with heavier rocket the numbers are 130 m/s, 200 and 600 m, respectively.

18 Depending on temperature, burn times of 5 and 10 ms were measured with a 64-mm M80 rocket that is similar to the one of the M72 (Zecevic et al., 2011).

19 NAVAIR, 2004a (several specifications outdated); NAVAIR, 2004b; Lance, 2006; Hatcher, 2007; Defense Update, 2010; NAVAIR, 2014b; NAVAIR, 2017.

The missile length is 0.635 m, the diameter is 57 mm, the mass is 2.4 kg. In a burn time under 1.5 s it is accelerated to a velocity of 270 m/s (high sub-sonic), the maximum firing range is 3.2 km. The warhead of 0.45 kg produces an explosively formed projectile. Inertial guidance, an electro-optical seeker, semi-active laser tracking and an RF data link are available. Test flights began in 2004, demonstrations with increasing difficulty followed, in 2016 UAVs were shot down. Other envisioned targets are small boats, helicopters, bunkers, machine gun nests and small armoured vehicles. The missile could be carried by UAVs, including small ones, uninhabited ground and water vehicles or shoulder-fired from a launch tube.

Raytheon Pike[20]

The US Raytheon company is developing a very small missile called Pike, presented publicly in 2015. With 40 mm diameter, 0.427 m length and 0.77 kg mass it carries a warhead of 0.27 kg that, using high-explosive fragmentation, has a lethal radius of 10 m. The missile is pushed out of the launcher, and at 2.5-3 m the rocket motor ignites, accelerating to 340 m/s in a fraction of a second. Its maximum range is 2 km. It can be carried by a single soldier, launched from existing or slightly modified 40-mm grenade launchers, e.g. underslung under a rifle. A second soldier designates the fixed or slowly moving target by a laser. Deployment on ground and air vehicles, in particular uninhabited ones, and on small boats is foreseen, too. A digital, semi-active laser seeker in the nose guides the missile to the illuminated spot, with accuracy on the order of a metre.

The Pike missile shows that miniaturised sensors and electronics can allow very small guided missiles with high precision. It may present one path of future missile development; e.g. the Turkish Yatagan missile, introduced 2019, has similar properties (see appendix A). With easy portability and low price, such systems would give many actors a missile capability.

20 Military.com, 2015; Dhingra, 2019: 302; Raytheon Missiles and Defense, 2015/2021.

7 Potential Military Uses of Small and Very Small Missiles

Carriers, Launchers

Small and in particular very small missiles and their launchers would be easier to use and require less training. They can be carried by single soldiers as well as by all kinds of traditional, inhabited combat vehicles (winged aircraft, helicopters, armoured and non-armoured land vehicles, ships and boats). Here they may be used for defence against approaching bigger missiles or maybe larger projectiles. Launchers can be small, containing one or two missiles, but for existing types there are also launchers for many missiles, carried on land, water (surface) and air vehicles. Smaller size and weight allow arming smaller uninhabited air, ground and surface vehicles, or in case of bigger ones, carrying more missiles per vehicle. Obviously this includes potential future autonomous weapon systems. A special use would be on satellites against approaching anti-satellite weapons, either satellites of the rendezvous type or fast direct-ascent missiles.

Damage Modes

Various modes of damage or destruction are possible and have been used, depending on the intended targets.[21] Against personnel and light, unarmoured (land, surface, air) vehicles, blast from a high explosive (HE) is effective, sometimes in the form of thermobaric (fuel air) explosive, where oxygen from the surrounding air acts as oxidator, allowing markedly higher energy per mass of explosive). High explosive can also be used to accelerate fragments, darts or flechettes (small steel arrows), that hit parts of the target. Explosive overpressure as well as metal provide a significant radius of destruction (metres to tens of metres, depending on warhead mass), thus the targeting accuracy needs to be on this scale.

Directly hitting the target with the missile would work, but requires very high accuracy, on the order of the target size. In our database the direct-hit mechanism is to be used with two missiles, the Miniature Hit-to-Kill (MHTK) and the SAVAGE systems, both in development by US firms (see appendix A). With miniaturisation of sensors and electronics, sophisticated guidance schemes are becoming feasible also for small and very small missiles.

For attacks against heavy armour traditional (small and not small) missiles use a shaped charge where a conical liner, often copper, is formed by an explosive into a fast jet that erodes the material and creates a thin, long hole. Typical penetration in steel is 4 to 6 times the diameter of the charge (depending on the standoff distance, about 20% less in rolled homogeneous armour than in mild steel) (Walters/Zukas, 1989: 179-180, 136). To penetrate

21 We exclude weapons of mass destruction here. Nuclear warheads with typically hundreds of kg mass would not fit on small and very small missiles; biological and chemical weapons are prohibited by the respective conventions and, due to very small payload, would produce limited effects.

heavy armour, many anti-tank missiles launched from a 40-mm tube have much thicker heads protruding from the tube.

Among the traditional missiles types in our database, we have found anti-armour shaped charges with warhead masses from 1.1 kg (S-5K, S-5K1) to 2.2 kg (Firos-6, SNIA 51), with outer diameters from 51 mm to 68 mm (the charge diameters may be slightly less), see appendix A. Using the proportionality mentioned, penetration depths around 300 mm should be possible. Actual penetration was given only rarely, e.g. for the Bulgarian S-5KP of 55 mm diameter 250 mm was found (Udoshi, 2019: 729), that is around 4.3 times the charge diameter.[22] For deeper penetration armed forces have to use bigger missiles (beyond the 69 mm limit of our database), e.g. the Bulgarian UARS-80 VMZ with 80 mm diameter is credited with 400-420 mm (Udoshi, 2019: 729), that is about 5 times the charge diameter.

The rough proportionality between charge diameter and penetration depth mentioned above used to not apply for charges with 40 mm diameter and below, "since for small charges precision tolerances are difficult to achieve" and because of a curved detonation wave (Walters/Zukas, 1989: 186). However, in present times probably both problems can be solved. Very small shaped charges are possible indeed: Motivated by the fictitious 'Slaughterbots' video (Future of Life Institute, 2017; Crowder/Russell, 2017), the Swiss Federal Office for Defence Procurement – armasuisse – built a shaped charge of about 2.5 cm diameter with 3 g of explosive with a conical copper foil that penetrated a human-skull simulant (Drapela, 2018, diameter from photo).

If the cone opening angle in a shaped charge is increased markedly, the velocity of the jet decreases until the latter converges with the slug formed from the main part of the metal liner. Such an explosively formed projectile can travel a considerable distance through air, the penetration depth in armour is on the order of the charge diameter; alternatively it can split into fragments (Bender & Carleone, 1993; Fong, 2004: 11). Such a mechanism is used in the Spike developmental missile (see appendix A).

Action by very small missiles against heavily armoured objects may be possible in the future if sophisticated guidance would allow to hit soft spots, such as the windows, optics, engine intakes or communication antennae.

Submunitions?

The UK Starstreak MANPADS High Velocity Missile, with 127 mm diameter and 14-17 kg mass far beyond our "small" category, uses three 'darts', guided sub-missiles of 22 mm diameter, 0.396 m length and 0.9 kg mass, that are separated at burnout and fly in a 1.5 m formation into the target where fragments are exploded (Widlund et al., 2019: 712-715). Because these darts are not independent missiles we do not include them in the database. In principle similar submunitions could be used with small missiles (diameter below 69 mm, mass a few kg) or even very small ones (up to 40 mm, below or around 1 kg), provided that suffiently accurate hits, maybe at sensitive spots, and and satisfactory damage could be achieved. Whether the additional development and system cost would appear justified is open at present.

22 For other types of 55 mm lower depths were given, not always consistent, e.g. the Bulgarian S-5KO is credited with 172 mm and 120 mm, respectively, on the same page (Udoshi, 2019: 729).

Swarms or Salvoes

Swarms of small and very small UAVs promise a significant increase in combat effectiveness (Pilch et al., 2021a: Chapter 6). Transferring this concept to small and very small missiles meets difficulties; due to their limited flight time the swarm manoeuvering capability would be strongly limited, including re-arrangement of the swarm elements as well as co-ordinated action reacting to movements or actions of the enemy. A more plausible notion would be that of a salvo where a multitude of missiles would be launched, maybe in time sequence, and attack a target from many sides, saturating defences. Whether here one bigger missile with a higher damage potential or a salvo of smaller ones will be more effective will depend on the details of the intended engagement, in particular the relative cost.

Countermeasures against Small or Very Small Missiles

Since the damage potential of small and very small missiles is limited, passive hardening should go a long way in protecting against them. With increasing accuracy special measures for protecting soft spots will gain importance. Depending on the missile guidance scheme, decoy methods (such as flares against infrared seekers) seem useful.

Active defence could try to interfere with the sensors or electronics, e.g. by microwave or laser pulses. Small and in particular very small missiles themselves – foreseen to attack incoming bigger missiles – could also be used against smaller ones. Also here relative cost, but also the cost-exchange ratio with respect to the attacking systems, will play a role.

8 Small and Very Small Missile Database

8.1 Database Properties

The missile (as well as the small and very small aircraft) databases are publicly available via https://url.tu-dortmund.de/pacsam-db as HTML tables. The tables are fully searchable and columns can be sorted. The data can be downloaded in .csv or .JSON file format by clicking on the CSV or JSON button. Empty cells indicate that no information was found. A screenshot of the web page is shown in Figure 8.1. The complete database is shown in appendix A. Additionally, all data files, including the interactive HTML file, are available under https://doi.org/10.5281/zenodo.5937585. The printed version here was updated on 30 December 2021.

According to our definition (section 2.2), all missile types listed have a diameter below 69 mm. All are armed. The missile database contains 24 categories, listed in table 8.1. In several cases – more as with small and very small aircraft – no information was found.

As mentioned in the introduction only public sources were investigated, consisting mainly of articles in the military press or catalogues such as the collections of Jane's (Dhingra, 2019; Udoshi, 2019; Widlund et al., 2019), the country-/organisation-specific lists in (CSIS, 2021)[23], or the Directory of U.S. Military Rockets and Missiles (Parsch, 2009)[24]. In some cases press statements or fact sheets published by manufacturers were used. Some information could be gained from dimensioned drawings and photographs in (CISR, 2004a, 2004b). Where other, original information had been removed or was too difficult to find we used Wikipedia entries. In some cases the missile specifications differed slightly between sources. There may be different reasons: conversion from imperial to international units; some missiles exist in different versions with different warheads and lengths or numbers of fins; the missile diameter may be sligthly less than the launch-tube diameter (usually taken as the calibre), e.g. a 55-mm missile launched from a 57-mm tube. We use numbers appearing most plausible, cautioning the reader that there may be inaccuracies. Since the sources often give incomplete specifications, the database is somewhat unsystematic. For example, the countries to which systems have been exported are missing from the "In service" entry in many cases. The number of fins is not always given explicitly, but can sometimes be seen on photos or sketches. If this entry is empty for one type, but another type of a family has one, this may hold for the former, too.

The focus of our investigation was on systems designed to be used in a combat context; practicing types, sometimes sub-calibre, were excluded. Research or development in other, e.g. academic, contexts, was not found. Patents or other ideas are not included (e.g. Rogoway, 2017).

23 Country lists of: China, France, Hezbollah, India, Iran, Israel, North Korea, Pakistan, Russia, South Korea, Taiwan, United Kingdom, United States. Here the smallest diameters occurred with MANPADS (a few systems with 71 or 72 mm), the other missiles had higher values, up to 760 mm.

24 Mainly Appendix 4: Undesignated Vehicles, mainly for older types.

Some types originally produced in the USSR were later produced in other countries such as Bulgaria (e.g. the S-5K types); where the specifications differ, they are listed separately.

In many cases the small or very small missiles found belong to families of which most members have bigger diameters, e.g. the Bulgarian RTB-7 family with thermobaric and smoke effects that has one type with 90 mm, three with 106 mm (Dhingra, 2019: 305-307). Only the illumination version RILL-7MA with 60 mm, atypical of its family, is included in the data base.

Some missiles – or rather grenades – have a charge for expelling them from the launch tube only, there is no rocket motor for further acceleration. Such is the case for the Bulgarian KO-7VMZ whereas the KO-7V, also with 57 mm diameter, has a rocket motor (Dhingra, 2019: 323-324). Consequently the first is not in the database while the second is. Similarly, of the Romanian OG-7 rounds with three versions (40 mm with HE/fragmentation, 60 mm with HEAT, 106 mm with thermobaric warhead) (Dhingra, 2019: 318), the first two come without a rocket motor and are not included;[25] the third has one, but is excluded because due to its diameter it is not a ”small” missile.

In the next section (8.2), we give a general overview of the data, with some statistics. In section 8.3 we present parameter distributions and correlations of technical parameters.

Table 8.1: The 24 categories used in the database of small and very small missiles.

Category	Description
Name	Name of the missile
Manufacturer	Name of the missile manufacturer
Origin	(First) manufacturer’s origin country
Intro	Year of introduction or of first mention in media
Status	Includes commercial availability, development, military deployment or already ordered by a nation for service, legacy (no longer produced by manufacturer), advertised by manufacturer, research stage and unclear if status information is missing or outdated
In service	Nations with military usage – import countries often incomplete
Mission	Mission of missile
Mass / kg	Mass at launch in kilograms
Length / m	Missile length in metres
Diameter / mm	Missile diameter in millimetres
Fins	(Maximum) number of fins, wings or canards (sometimes two sets)
Fin span / mm	(Maximum) span of fins, wings or canards in millimetres
Range / km	Maximum flight range in kilometres (effective, ballistic maximum can be markedly larger) (sometimes unclear which one given)
Speed / m/s	Speed at burnout in metres per second
Propulsion	Method of thrust generation
Thrust / N	Motor thrust in newtons
Burn time / s	Motor burn time in seconds

25 It is interesting that for these two the expelling charge is sufficient for a range of 1,000 and 1,500 m, respectively (Dhingra, 2019: 309).

Launch	Launch method
Guidance	Navigation/guidance method
Targeting	Targeting capabilities, e.g. laser tracking, radar seeker
Target class	Classes of targets
Warhead	Type of warhead, possibly with mass
Fuse	Type of fuse
References	Data sources

Preventive Arms Control for Small and Very Small Armed Aircraft and Missiles

List of small and very small missiles below 69 mm diameter

Researcher: Jürgen Altmann
Research Director: Dieter Suter
Project website: https://url.tu-dortmund.de/pacsam

In case of errors or questions, please do not hesitate to contact us.

Please note that the sorting algorithm works by lexicographic order and may yield improper results for columns which include mixed data types.

Last update: 30.12.2021

JSON CSV SEARCH:

Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Ra
NORINCO	China		Deployed	China	Air-to-ground	3.99	0.91	55	yes	230	5
Thales/TDA	France	2013	Deployed	France	Air-to-ground	8.8	1.39	68	8	240	6
Thales/TDA	France	2009	Deployed	France	Air-to-ground	7.5	1.39	68	8	240	6
SITEA	Argentina		Deployed	Argentina	Air-to-ground	5.0	0.76	57	4	150	
KBP	Russia	2012	Deployed			3.5	0.742	62	4		0.
NORINCO	China	1984	Deployed	China, Sri Lanka		5		62	6		
BPD Difesa E Spazio/ Nexter	Italy	1981	Deployed, production ceased	Italy, Mexican Marine Corps	Ground-to-ground	4.8	1.05	51	4		6.
Sakr	Egypt		Deployed	Egypt		1.75	0.612	40			0.
	Taiwan	2015	Deployed	Taiwan	Anti-tank, anti-structure	1.4		67			0.

SHOWING 1 TO 50 OF 50 ENTRIES

Notes

Empty cells indicate that no information was found from public sources.

Categories

Status

Deployed
Reported to be deployed in a nation's military service.

On offer
Actively advertised by manufacturer, e.g. online.

Production
Reported to be in production.

Production ceased/No longer advertised

Figure 8.1: Screenshot of the small and very small missile database available at https://url.tu-dortmund.d/pacsam-db-sm.

8.2 General Overview

A general overview of the missile types found is given in Figure 8.2. Of the 50 types 39 are in the "small" category and 10 count as "very small". They are produced by 26 manufacturers in 17 countries. 41 types are deployed while only 5 are in development. It is notable that none was found in the stage of research, a marked difference to small aircraft where there is considerable acacemic research (Pilch et al, 2021a).
Figure 8.3 shows the numbers introduced in five-year periods between 1950 and today.[26] Higher activities are visible in the 1950s and 1980-2000 and after 2010. Of the 32 types for which a year of introduction was found, 16 appeared before 1990, 9 after 2010.

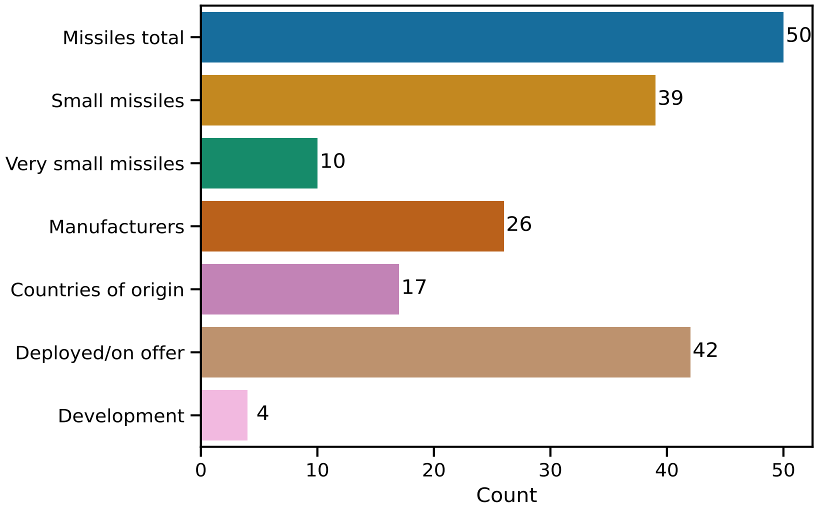


Figure 8.2: General properties of the database.

26 Here "1980s" was assigned to 1985 and "1990s" to 1995.

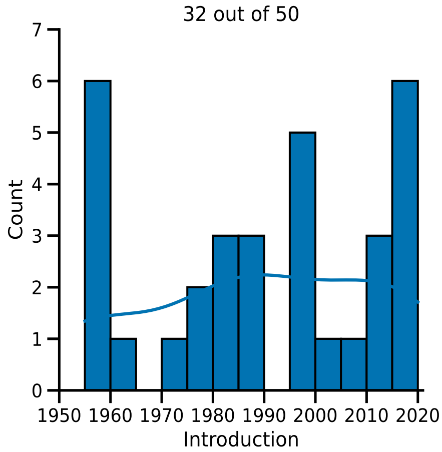


Figure 8.3: Number of types over years of introduction, bin width 5 years (not for all types a year of introduction was found). The curve shows a Gaussian kernel distribution estimation.

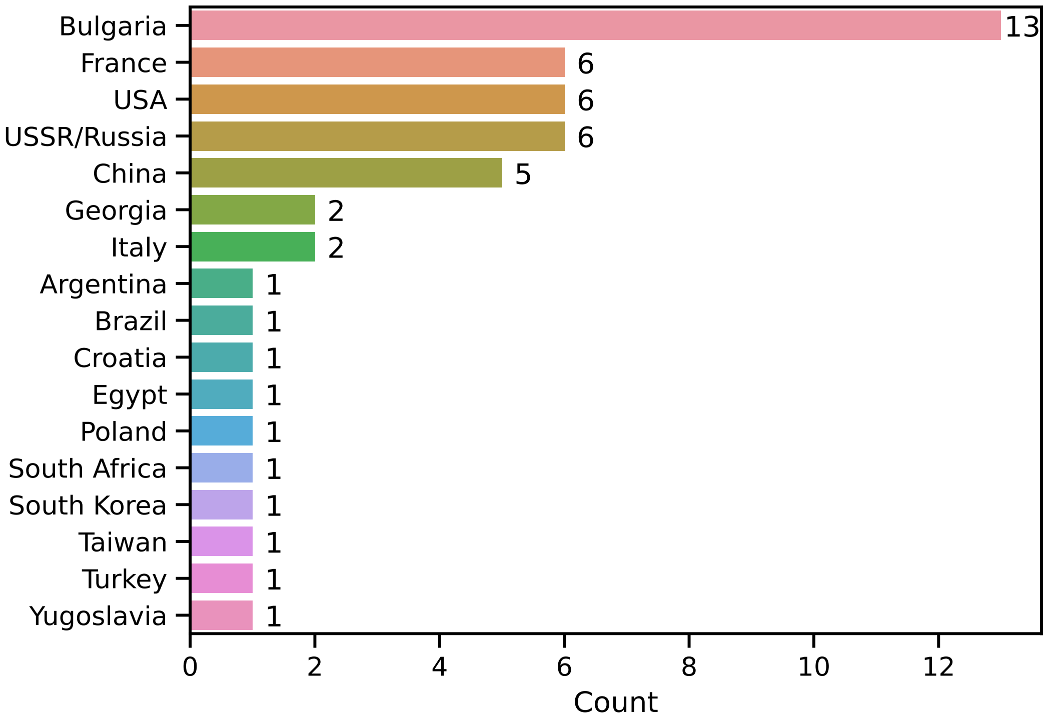


Figure 8.4: Number of types per country.

The number of types per country is shown in Figure 8.4. The high numbers of Bulgaria, Russia and China are mainly caused by the variety of old missile families produced in these countries. It is interesting that the USA is not dominating here.

8.3 Parameter Distributions and Correlations

In this section we present distributions of important parameters singly as well as one versus another. Different from the case of aircraft, which were separated by different kinds (e.g. fixed/rotary wing, armed/unarmed) (Pilch et al., 2021a), all missiles are counted as being of the same kind.

Figure 8.5 shows the distribution of diameters. One cluster is around 40 mm (with 10 types “very small”, i.e. with diameter up to 40 mm), another between 55 and 68 mm. Only one type lies below 40 mm (the Brazil SBAT-37, introduced in the 1970s or 1980s, see appendix A), the other 9 very small types have 40 mm.

The distribution of ranges is presented in Figure 8.6. The conspicuous peak around 0.2 km is caused by the high number of shoulder-fired anti-tank missiles.

In the distribution of masses (Figure 8.7) there are clusters around 2 kg and around 5 kg.

Figure 8.8 shows that during the decades from 1950 to the present, many missiles of different diameters in the range considered (≤ 40 mm to < 69 mm) were developed, without a time trend toward a sub-range of that.

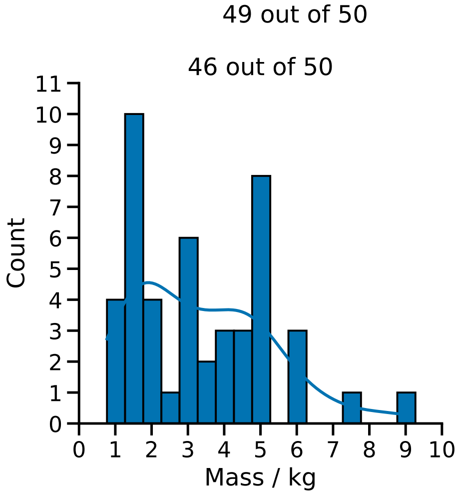


Figure 8.7: Mass distribution. The bin width is 0.5 kg, the curve represents a Gaussian kernel density estimation.

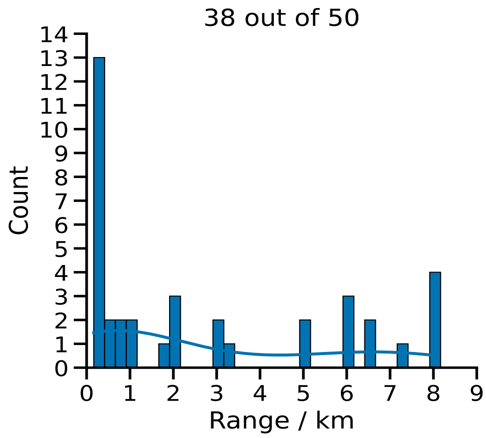


Figure 8.6: Range distribution. The bin width is 0.25 km, the curve represents a Gaussian kernel density estimation.

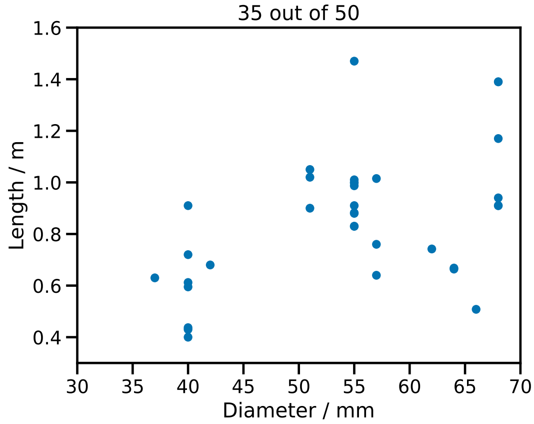


Figure 8.9: Length versus diameter.

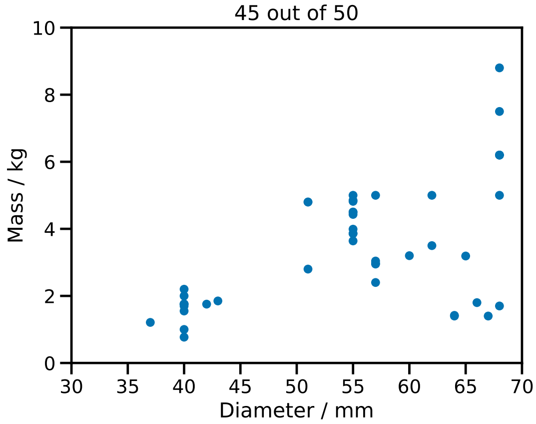


Figure 8.10: Mass versus diameter.

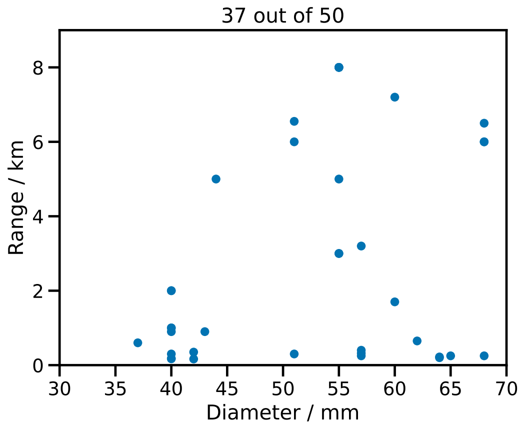


Figure 8.11: Range versus diameter.

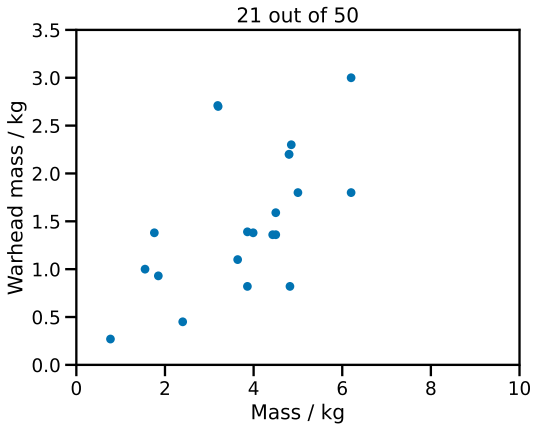


Figure 8.12: Warhead mass versus mass. Two outliers at the same spot have an unusually large warhead-mass ratio (85%, 2.7 kg of 3.2 kg) and a speed at the lower end (see text).

Figure 8.9 shows the length versus the diameter; not unexpectedly, the length increases with the diameter, but with much variability. Similarly, Figure 8.10 (mass versus diameter) demonstrates that also the mass increases with the diameter. Also the range generally increases with the diameter (Figure 8.11, range versus diameter), but there also are types of all diameters with very short ranges. The final Figure 8.12, showing the warhead mass versus the (launch) mass, demonstrates that typically the warhead mass is one third to one half of the total mass. However, there are two outliers where the values are 2.7 kg of 3.2 kg, that is the warhead has 85% of the mass. These are the Bulgarian RILL-7MA with illumination warhead and the Bulgarian RHEF-7LDMA with high explosive/fragmentation warhead; with 100 m/s their speed is at the lower end, reflecting a lower fuel portion (see their database entries in appendix A).

9 Conclusion

Small missiles (diameter below 69 mm and above 40 mm) have been in the arsenals since decades, used for various purposes, many unguided, but since the 1960s and 1970s increasingly guided. However, the great majority of missile types has bigger or much bigger diameters. Very small missiles (up to 40 mm) in the past have played only a marginal role, often as special versions of families for 40-mm launchers where most members have markedly thicker warheads, all unguided. But in the 2010s, specific new types with 40 mm diameter have begun to appear, guidance provided by various principles (e.g. sensors in the front seeking a laser spot or commanded from a ground radar station).

Small and very small missiles have been developed and are produced by at least 26 manufacturers in at least 17 countries.

There is a big difference between small and very small missiles and small and very small aircraft. Except for hobbyists' models, the latter have only appeared in the recent decade, and there is much research and development going on, including in academia. Many missiles, on the other hand, date back several decades. Very little research seems to be done, and development is limited. Part of the reason for the difference may be that there are fundamentally different aircraft configurations – using fixed, rotary or flapping wings, and different modes of propulsion. Conversely, missiles nearly exclusively use one long-established scheme: circular body, rocket propulsion, control fins. The difference is reflected in the lower number of missile types (50 in our missile database, at least 17 of which appeared before 1990), compared to the 152 types in the updated aircraft database of which at least two thirds were introduced in or after 2000 (see Pilch et al., 2021c).

Small missiles have masses from 2.4 to 8.8 kg, very small ones from 0.8 to 2.2 kg. Typically the warhead masses are one third to one half of the total mass. The maximum effective ranges[27] vary from less than 0.2 km (for shoulder-fired anti-tank missiles) to many kilometres (for launch from the air or against air targets, but also for ground-to-ground missions). Speeds (at burnout) are from 100 to 670 m/s, that is from 0.3 to 2 times the speed of sound. Correspondingly the flight times range from about 1 second for 0.1-0.2 km to above 10 seconds for many kilometres. Manoeuvering is possible over such flight durations; if a target was not hit within this time, the missile cannot turn and select another target.

Due to low payload masses and short ranges, the military effectiveness of small and very small missiles will remain limited. Development in the area of missiles will rather focus on larger systems. But for certain missions small and very small systems provide new options, e.g. for arming small uninhabited vehicles or for defence against incoming missiles. With very high accuracy they could put larger, including armoured, systems at risk. Thus military interest in them will likely continue and may lead to more sophisticated guidance systems and in general increased development and deployment.

27 The maximum ballistic range may be considerably longer, but here the speed may be too low for fast manoeuvering, guidance may no longer be reliable, or programmed self-destruction occurs.

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A Table of Small and Very Small Missiles

On the following pages, the complete missile database is presented in table format. We recommend using the interactive online version available at https://url.tu-dortmund.de/pacsam-db-sm instead, which allows searching and sorting. Additionally, all data files, including the interactive HTML file, are available under https://doi.org/10.5281/zenodo.5937585. (Altmann & Suter, 2022). The printed version here was updated on 30 December 2021.

Name	Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Range / km	Speed / m/s	Propulsion	Thrust / N
57-1 / 57-2	NORINCO	China		Deployed	China	Air-to-ground	3.99	0.91	55	yes	230	5		Rocket	
Aculeus guided	Thales/TDA	France	2013	Deployed	France	Air-to-ground	8.8	1.39	68	8	240	6		Rocket	
Aculeus unguided	Thales/TDA	France	2009	Deployed	France	Air-to-ground	7.5	1.39	68	8	240	6		Rocket	
ASPID 1057	SITEA	Argentina		Deployed	Argentina	Air-to-ground	5	0.76	57	4	150			Rocket	
BUR	KBP	Russia	2012	Deployed			3.5	0.742	62	4		0.65	99 / 98	Rocket	
FHJ-84	NORINCO	China	1984	Deployed	China, Sri Lanka		5		62	6			126	Rocket	
Firos 6	BPD Difesa E Spazio/ Nexter	Italy	1981	Deployed, production ceased	Italy, Mexican Marine Corps	Ground-to-ground	4.8	1.05	51	4		6.55	515	Rocket	1960
Home Guard	Sakr	Egypt		Deployed	Egypt		1.75	0.612	40			0.3	154	Rocket	
Kestrel		Taiwan	2015	Deployed	Taiwan	Anti-tank, anti-structure	1.4		67			0.40 / 0.15		Rocket	

Burn time / s	Launch	Guidance	Targeting	Target class	Warhead	Warhead mass / kg	Fuse	ReferencesShort
	Multiple launcher	None		Various	HE	1.38	Jian-Yin-4	Udoshi (2019): 734-736.
1	2, 8, 12 multiple launcher	Inertial	Semi-active laser seeker	Various	Air burst + blast, HE-multimode		Impact, proximity	Udoshi (2019): 736-739.
1	2, 8, 12 multiple launcher	None	None	Various	Multi-dart, HE-impact, HE-multimode		Impact, proximity	Udoshi (2019): 736-739.
43	6-multiple launcher	None			HE, frag., HEAT			Udoshi (2019): 715.
	GK-62.01 launcher	None			HE, HE frag.		Impact	Dhingra (2019): 316, "BUR" (2021).
	Twin tube, multiple shot	None	Sight		Incendiary, smoke			sassik (2013), Military Today (no date, FHJ-84), Wikipedia (2021, FHJ-84).
1.1	Multiple launcher	None	None		HEAT/AP, frag., HE incendiary, illumination, smoke	2.2	Various	Widlund et al. (2019): 349-350, Dhingra (2019): 903.
	RPG-7 type launchers	None			Frag.		O-4M impact	Dhingra (2019): 323.
	Tube, portable	None	Sight	Tanks, structures	HEAT, HESH			Military Today (2016, Kestrel), Wikipedia (2021, Kestrel).

Name	Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Range / km	Speed / m/s	Propulsion	Thrust / N
KO-7V	VMZ	Bulgaria		Production			2.97	1.015	57			0.4	98	Rocket	
Kodori-3	Delta	Georgia		Deployed	Georgia		1.85		43			0.9		Rocket	
Kodori-4	Delta	Georgia		Deployed	Georgia		1.55		40			0.9		Rocket	
M72	NAMMO	USA	1963	Deployed	USA + 39 others	Anti-tank	1.8	0.508	66	6-8		0.20-0.35	130-200	Rocket	
M72 ASM RC	NAMMO	USA		Deployed	Finland, probably others	Anti-structure			42			0.35	170	Rocket	
M80 Zolja	Sloboda Čačak	Yugoslavia	1980s	Deployed	Bosnia-Herzego-vina, Indonesia, North Macedo-nia, Montenegro, Serbia	Anti-tank	1.42	0.664	64	8	196	0.22	190	Rocket	
Mini missile	LIG Nex1	South Korea	2019	Develop-ment			2		40	4+4		2			
Miniature Hit-to-Kill (MHTK)	Lockheed Martin	USA	2013	Develop-ment		Surface-to-air	2.2	0.72	40	4	71			Rocket	

Burn time / s	Launch	Guidance	Targeting	Target class	Warhead	Warhead mass / kg	Fuse	ReferencesShort
	RPG-7 type launchers	None			HEAT/frag.		VP-22M piezoel. nose-mounted	Dhingra (2019): 323-324.
	RPG-7 type launchers	None			HE frag.	0.93		Dhingra (2019): 313-314.
	RPG-7 type launchers	None			HE frag.	1		Dhingra (2019): 313-314.
0.005-0.010	Tube, portable, single use		Sight	Tanks, structures	HE, HEAT, frag.		Contact	Cooke (2008), NAMMO (2018), Wikipedia (2021, M72).
	Tube, portable, single use	None	Sight	Structures	HE		Contact	NAMMO (2018), Wikipedia (2021, M72).
0.005-0.010	Tube, portable, single use	None		Tanks	HEAT			CISR/NEO (2004, M80), Zecevic et al. (2011), Balkan war history (2016), Military Today (no date, M80).
			Image infrared seeker, uncooled thermal seeker	Light armour, infantry	HEAT, frag.			Valpolini (2019).
	Truck-mounted missile launcher	Passive/active radar		Missiles, artillery, mortars and UAVs	Hit-to-kill		None	Lockheed Martin (2018a), Adams (2018), Trevithick (2018), Lockheed Martin (2018b), Wikipedia (2019, MHTK).

Name	Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Range / km	Speed / m/s	Propulsion	Thrust / N
Obstacle Breaching	NORINCO	China		Deployed	China		2.8	0.9	51	4		0.3		Rocket	
OFG-7V	VMZ	Bulgaria		Deployed	Bulgaria		2.95		57	4		0.25	99	Rocket	
OFG-7VM	VMZ	Bulgaria		Deployed	Bulgaria		3.04		57	4		0.32	98	Rocket	
OG-7V / OG-7VM	VMZ	Bulgaria	1978	Deployed	Bulgaria		1.76	0.595	40	4		0.17	152	Rocket	
OG-7VMZ	VMZ	Bulgaria	1978	Deployed	Bulgaria		1.755	0.68	42	None		0.165	152	Rocket	
Pike	Raytheon	USA	2015	On offer		Surface-to-surface, air-to-surface	0.77	0.43	40	4		2	340	Rocket	
QN-202	Guide Infrared	China	2018	Unclear		Surface-to-surface	1.2		c. 40	4+4		2			

Burn time / s	Launch	Guidance	Targeting	Target class	Warhead	Warhead mass / kg	Fuse	ReferencesShort
	RPG-7 type launchers	None		Matériel				Dhingra (2019): 310-312.
	RPG-7 type launchers	None			Frag.		O-4M impact	Dhingra (2019): 309.
	RPG-7 type launchers	None			HE frag.		O-4M impact	Dhingra (2019): 309.
	RPG-7 type launchers	None			Frag.		O-4M impact	Dhingra (2019): 309.
	RPG-7 type launchers	None			Frag.		O-4M impact	Dhingra (2019): 309.
Fraction of s	Underslung 40 mm grenade launcher, UAV, ground vehicles, remotely-operated weapons station, small boats		Semi-active laser seeker		HE frag.	0.27		Military.com (2015), Dhingra (2019): 302, Raytheon Missiles and Defense (2015/2021).
	Custom grenade launcher	Image self-guidance	Lock-on before launch, fire and forget					Eshel (2018), Hrachya (2018).

Name	Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Range / km	Speed / m/s	Propulsion	Thrust / N
RF-7MA / OGi-7M	Arsenal	Bulgaria		Deployed	Bulgaria		1.76	0.437	40			0.18	152	Rocket	
RH ALAN 60 mm	RH ALAN	Croatia		Deployed, production ceased	Croatia	Ground-to-ground			60			7.2		Rocket	
RHEF-7LDMA	Arsenal	Bulgaria		Deployed	Bulgaria		3.19		65	4		0.25	100	Rocket	
RILL-7MA	Arsenal	Bulgaria		Deployed	Bulgaria	Ground-to-ground	3.2		60			1.7	100	Rocket	
RO 68 HE-APERS	Mechem/Denel	South Africa		Deployed, production ceased	South Africa	Ground-to-ground			68	8		6.5		Rocket	
RPG-18 / Mukha	Bazalt etc.	USSR	1972	Deployed	Russia + 20 others	Anti-tank	1.4	0.668	64	4	208	0.2	115	Rocket	
RPG-76 Komar	Precision Works	Poland	1985	Deployed, production ceased	Poland	Anti-tank	1.7		68			0.25	145	Rocket	

Burn time / s	Launch	Guidance	Targeting	Target class	Warhead	Warhead mass / kg	Fuse	ReferencesShort
	RPG-7 type launchers	None			Frag.	1.38	AF76 / AF72 point detonation	Dhingra (2019): 307-308.
	4 launch vehicle	None			HE			Widlund et al. (2019): 321-322.
	ATGL-I family, RPG-7 type launchers	None			HE frag.	2.71	AF76 point detonation	Dhingra (2019): 307-308.
	40 mm ATGL-L2, Russian RPG-7V	None			Illuminating	2.7	AF612 or MTSQ DM93-2	Dhingra (2019): 305-307.
	6-/12-tube launcher	None	None		HE frag.		Proximity, contact	Dhingra (2019): 903-904.
	Tube, portable, single use	None	Sight	Tanks	HEAT			Becz (2011), Russian Combat Small Arms (2018), Military Today (no date, RPG-18), Wikipedia (2021, RPG-18).
	Tube, portable	None	None	Tanks	HEAT			Wikipedia (2021, RPG-76).

Name	Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Range / km	Speed / m/s	Propulsion	Thrust / N
S-5K	Kintex	Bulgaria	1990s	Deployed	Bulgaria	Air-to-ground	4.5	0.83	55	8	275		550	Rocket	
S-5K / S-5K1	Tochmasch	USSR	1955	Deployed	Russia, Allies	Air-to-surface	3.64	0.83	55	8	232	8	543	Rocket	
S-5KO	Tochmasch	USSR	1955	Deployed	Russia, Allies	Air-to-surface	4.43	0.987	55	8	232	8	586	Rocket	
S-5KO	Kintex	Bulgaria	1990s	Deployed	Bulgaria	Air-to-ground	4.5	1.01	55	8	275		586	Rocket	
S-5KP	VMZ, Armaco	Bulgaria	1990s	Deployed	Bulgaria	Air-to-ground	5	1.47	55	8	275		500	Rocket	
S-5M	VMZ, Armaco	Bulgaria	1990s	Deployed	Bulgaria	Air-to-ground	3.86	0.88	55	8	275	3	673	Rocket	
S-5M / S-5M1 / S-5S	Tochmasch	USSR	1955	Deployed	Russia, Allies	Air-to-surface	3.86	0.882	55	8	232	8	550-673	Rocket	
S-5MO	Tochmasch	USSR	1955	Deployed	Russia, Allies	Air-to-surface	4.82	0.998	55	8	232	8	543	Rocket	

Burn time / s	Launch	Guidance	Targeting	Target class	Warhead	Warhead mass / kg	Fuse	ReferencesShort
	Multiple launcher	None			HEAT	1.59	V5-K mech. contact	Udoshi (2019): 728-730.
1.1	8-32 multiple launchers	None			HEAT	1.1	Point detonation	CISR/NEO (2004, S-5a), CiSR/NEO (2004, S-5b), Udoshi (2019): 762-763.
1.1	8-32 multiple launchers	None			HEAT/frag.	1.36	Point detonation	CISR/NEO (2004, S-5a), CISR/NEO (2004, S-5b), Udoshi (2019): 762-763.
	Multiple launcher	None			HEAT/frag.	1.36	V5-K mech. contact	Udoshi (2019): 728-730; Arcon (2021).
	Multiple launcher	None			HEAT/frag.		V5-K mech. contact	Udoshi (2019): 728-730.
	Multiple launcher	None			HE	1.39	V5-M contact	Udoshi (2019): 728-730.
1.1	8-32 multiple launchers	None			HE, frag., AP flechette	0.82	Point detonation	CISR/NEO(2004, S-5a), CISR/NEO (2004, S-5b), Udoshi (2019): 762-763.
1.1	8-32 multiple launchers	None			HE, frag.	0.82	Point detonation	CISR/NEO (2004, S-5a), CISR/NEO (2004, S-5b), Udoshi (2019): 762-763.

Name	Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Range / km	Speed / m/s	Propulsion	Thrust / N
S-5MO	VMZ, Armaco	Bulgaria	1990s	Deployed	Bulgaria	Air-to-ground	4.85	1	55	8	275	3	543	Rocket	
SAVAGE	SAVAGE Corp.	USA	2020	Develop-ment	None	Surface-to-air	< 0.9		44	4+4		5	400	Rocket	
SBAT-37	Avibras	Brazil	1970s/ 1980s	Deployed, production complete	Brazil	Air-to-surface	1.21	0.63	37	4		0.6		Rocket	
SNEB 68-253	Thales/TDA	France	1955	Deployed	France, others	Air-to-ground	5	0.91	68	8	240	Kilo-metres		Rocket	4200
SNEB 68-259LEM	Thales/TDA	France		No longer advertised	France, others	Air-to-ground	6.2	1.17	68	8	240	Kilo-metres		Rocket	
SNEB AMV / SNEB AML	Thales/TDA	France	1984	Deployed	France, others	Air-to-ground	6.2	0.94	68	8	240	Kilo-metres		Rocket	5000
SNEB HE-IMP	Thales/TDA	France	1955	Deployed	France, others	Air-to-ground	6.2	0.91	68	8	240	Kilo-metres		Rocket	4200
SNIA 51	SNIA/SNIA BPD	Italy	1980s	Deployed, production ceased	Italy, others	Air-to-ground	4.8	1.02	51	4	120	6	470	Rocket	2050

Burn time / s	Launch	Guidance	Targeting	Target class	Warhead	Warhead mass / kg	Fuse	ReferencesShort
	Multiple launcher	None			HE/frag.	2.3	V-5K mech. contact	Udoshi (2019): 728-730.
	4, 64 multiple launcher		Video processing	UAV swarms	Hit-to-kill, HE			SAVAGE (2020a), SAVAGE (2020b).
	7 multiple launcher	None			HE			FORÇA AÉREA BRASILEIRA (2006), Lexicar Brazil (2014), Udoshi (2019): 726-727.
0.8	8, 12, 22, 36 multiple launcher	None	None	Various	HEAT	1.8	Impact, piezoelectric	Udoshi (2019): 739-742.
		None	None	Various	ECM chaff, multi-band decoys			Udoshi (2019): 739-742.
1	8, 12, 22, 36 multiple launcher	None	None	Various	36 / 432 multi-darts	1.8	Time delay	Udoshi (2019): 739-742.
0.8	8, 12, 22, 36 multiple launcher	None	None	Various	HE blast, frag.	3	Impact, piezoelectric	Udoshi (2019): 739-742.
1.1	Multiple launcher	None	None	Various	HEAT/AP, frag., HE incendiary	2.2	Point detonating, base detonating	Udoshi (2019): 755-756, Wikipedia (2021, BPD).

Name	Manufacturer	Origin	Intro	Status	In service	Mission	Mass / kg	Length / m	Diameter / mm	Fins	Fin span / mm	Range / km	Speed / m/s	Propulsion	Thrust / N
Spike	Naval Air Warfare Center, Weapons Division	USA	2004	Develop-ment		Surface-to-air, surface-to-surface	2.4	0.64	57	4		3.2	270	Rocket	
WR-2004	NORINCO	China		Deployed	China		1.7	0.91	40	4		1	175	Rocket	
Yatagan	Roketsan	Turkey	2019	On offer		Surface-to-surface, air-to-surface	1	0.4	40	4+4		1			

Burn time / s	Launch	Guidance	Targeting	Target class	Warhead	Warhead mass / kg	Fuse	ReferencesShort
< 1.5	2.25 kg shoulder launcher, UGV, UAV, boat or ship	Electro-optical TV tracker, inertial , laser spot tracker, RF data link	EO, semi-active laser seeker	Small boats, helicopters, aircraft, lightly armoured vehicles, mobile targets	Explosively formed projectile, blast fragmentation, solid fuel air explosive	0.45	Contact	NAVAIR (2004a), NAVAIR (2004b), Lance (2006), Hatcher (2007), Defense Update (2010), NAVAIR (2014), NAVAIR (2017).
	RPG-7 type launchers	None			HE frag.			Dhingra (2019): 310-312.
	Underslung grenade launcher		Semi-active laser seeker					YATAĞAN (2019).

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