Missile Identification and Assessment

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Introduction

This paper is intended as an introduction to basic concepts of missile technology, which will allow readers to better understand the threat potential of a ballistic-missile system by applying basic analysis methods. This increased understanding may support policymakers in decision-making processes concerning ballistic-missile threats.

Ballistic missiles are viewed by many states as a means to project power regionally and in some cases globally, and they are an important element in many national deterrence doctrines. Ballistic missiles are not a new phenomenon, but the diffusion of the technological equipment and the technical knowledge to develop them has meant that more states than ever now operate them. Correspondingly, improvements in the guidance technology used in many modern missiles to facilitate their employment in conventional precision strikes mean that ballistic missiles are no longer only suitable for the delivery of weapons of mass destruction (WMD). Improvements in the accuracy and availability of ballistic missiles have driven their utility, which might in turn spur their utilisation given that they pose a low risk to service personnel and provide an opportunity to fulfil military or political objectives. Understandably, specialists and policymakers working in the field of arms control and technologies are increasingly focused on identifying and assessing these capabilities and their possible implications.

This technical analysis will provide specialists and policymakers with a beneficial understanding of the technology that underpins and influences ballistic-missile design. Additionally, this paper will provide analysts with tools that can be applied to examine and draw initial conclusions about a ballistic missile’s capabilities, using the increasing amount of open-source material available on ballistic missiles. This should benefit the quality of debate, provide a better understanding of missile technology and give those interested a simple method of conducting an initial missile analysis.

The paper is divided into four sections: the first introduces the reader to some of the fundamental elements of rocketry, including propulsion, airframes, guidance and flightpaths. The second section briefly unpacks proliferation and the spread of missile technology, providing a useful background for understanding how missile programmes develop and take different forms over decades, involving licensed and unlicensed variants. The paper then provides a guide to credible information to consider when analysing missile systems and explains why this information is useful. Finally, it presents an analysis of a typical ballistic missile. This provides a working example that analysts can replicate when conducting an examination and assessment of missile systems in the future.
Chapter One: Ballistic Missile Technology 101

A ballistic missile is strictly speaking not a weapon in itself. Rather, the missile is a delivery system that is designed to deliver a payload, commonly referred to as a warhead – which might, for instance, be a nuclear weapon, a chemical agent or high explosives – to an intended target where it unleashes its destructive power. To perform this task, the missile must carry a certain amount of weight (its payload) over a certain distance (its range). The missile must do so with a sufficient level of accuracy to ensure that it is able to place the weapon charge close enough to the target to cause sufficient damage.

Even when it includes the warhead, a missile is not an operationally capable system. All ballistic missiles require a launch system, as well as support systems. These include specially designed vehicles for transporting and fuelling the missile, a dedicated command-and-control unit, sub-systems for inputting target information, dedicated equipment for communications and for conducting meteorological surveys, along with a crew to operate each element of the overall system.

Figure 1: Weapons and delivery systems

Only this combination of payload (warhead), delivery system (rocket) and launch and support systems constitutes an operational missile system. Without these elements, the missile alone is useless.

The missile

A ballistic missile has four elements, each of which serves a specific purpose:

- **Propulsion** powers the missile and determines its range and payload.
- **The airframe** is the dead mass that houses all the internal systems.
- **Guidance and control** keeps the missile on track while it flies toward its target.
- **The payload** includes everything that is to be delivered to the target.

Propulsion

Propulsion is often seen as the core of a missile. Propellants are burned in the rocket's combustion chamber and the resulting energy ejects the hot gas that is produced out of the chamber at high speed. A simple analogy for this process is a gunshot, where a projectile is fired from a gun and the recoil pushes the gun in the opposite direction.

If this gun is continuously fired, it will accelerate in one direction while projectiles come out in the other
direction. Rather than carrying both heavy projectiles and the gunpowder to propel them (when only the gunpowder carries energy that is released and converted into movement), a missile simply carries a refined gunpowder. When burned in the combustion chamber, this gunpowder produces molecules of hot gas that take over the role of the projectiles.

These gases stream out of the back of the combustion chamber continuously. According to fluid mechanics, the gases will accelerate on their way out if the ‘barrel’ becomes increasingly narrow, just like water flows more quickly at narrow passages in a river, thus creating rapids. However, this phenomenon stops when the gases reach their speed of sound and they will not move any more quickly by reducing the width of the ‘barrel’ further. But at this point, another phenomenon comes into effect: the gases accelerate when the ‘barrel’ widens again. These processes have prompted engineers to add a nozzle to the end of the combustion chamber. This way, the gases accelerate further, allowing them to leave the rocket at a very high speed. The speed of these gases – known as the exhaust velocity (c) – is an important parameter in rocketry.

Returning to the gun analogy, a cannon firing an artillery round should have more recoil than a rifle firing a bullet. The same is true for rocket propulsion: the more mass (m) that flows out of the nozzle (at the same speed) per second, the higher the thrust (F) forward. Two factors therefore influence the thrust level: mass flow (ṁ) and exhaust velocity. For any given rocket engine, analysts can theoretically simply reduce or increase the level of thrust by changing the mass flow. Nowadays, the thrust is usually given in kilonewton (kN), but it can easily be converted back and forth into kilograms (kg) or tonnes (t) with the value of Earth’s standard gravity (g₀), which is 9.80665 metres per second squared (m/s²). Kilograms and tonnes are much more illustrative than newtons as a unit for thrust: a rocket with 5 t of thrust will lift off its launch pad if the rocket itself weighs less than 5 t; if the rocket weighs exactly 5 t, it will simply hover in the air.

Dividing the exhaust velocity (in m/s) by Earth’s standard gravity provides an even better known value, with seconds (s) as a unit: the specific impulse (Iₚ). The specific impulse shows at a glance how well the rocket converts its propellants into thrust, which propels it forward. It therefore serves as a measure for rocket propulsion efficiency.

To illustrate this point, if a rocket engine offers a specific impulse of 300 s, it means that this engine could – in theory – generate 1 kg of thrust with 1 kg of propellants over a duration of 300 seconds. Engines with higher impulses are better as they provide greater thrust over time from the rocket’s limited propellant mass.
Rocket propulsion also works in a vacuum, meaning it is not dependent on air for combustion. Rockets therefore require two types of propellants: a fuel and an oxidiser to react with the fuel. Depending on the properties of the propellants, the propulsion systems may need to be designed differently. For liquid propellants, there are liquid-fuelled rocket engines and for solid propellants there are solid-fuelled rocket motors. There also are hybrid rocket motors, however these are not typically used for ballistic missiles and will therefore not be detailed in this paper.

**Liquid-fuelled engines and liquid propellants**

Almost a century after Robert Goddard launched his first liquid-fuelled rocket, his propellant mix of gasoline and liquid oxygen is still used for space launchers today. Developments in the field of liquid propellants over the past seven decades have been slight. Considering the vast variety of possible propellants and combinations for liquid-fuelled engines, only a handful are used for ballistic missiles for various reasons. The most common fuels used today include kerosene, various types of hydrazines and – though rarely used nowadays – a mix of particularly volatile chemicals referred to as ‘Tonka’ or ‘Samin’. Even fewer oxidisers are used for missiles: nitric acid (usually as inhibited red-fuming nitric acid [IRFNA]) and nitrogen tetroxide (NTO), which may also contain several additives, are the most common. Liquid oxygen was used for missiles in the 1940s and 1950s, but since it is only liquid at cryogenic temperatures below -183°C, its use has declined for obvious operational reasons. The other mentioned propellants are all liquid at room temperature and are therefore referred to as storable propellants. Using NTO is little problematic for the personnel operating the system because it is only liquid between -11 and +21°C, meaning it will freeze on a cold winter day and boil on a mild summer day. Adding additives, thus creating one of the Mixed Oxides of Nitrogen (MON) family, only moves the small operational window up or down slightly.

Oxidiser and fuel must be stored onboard the rocket in separate tanks. During the flight, the propellants somehow need to be moved from these separate tanks into the combustion chamber. Since the pressure in the chamber is quite high, usually ranging from 30 bar to more than 200 bar, the propellants must be injected at a very high pressure that significantly exceeds the pressure in the combustion chamber. This can be done by pressurising the tanks themselves to an even higher pressure. However, this process requires very strong tanks, which in turn add additional weight to the rocket – a situation that engineers wish to avoid at all costs. Therefore, above a certain performance level, the only practical way to move the propellants is through the use of turbopumps. These can be powered in different ways, which will not be detailed here.

High-performance liquid-fuelled rocket propulsion therefore needs tanks for fuel and oxidiser, turbopumps, as well as the actual engine (and some additional elements including piping, vents, valves and sensors).

**Solid-fuelled motors and solid propellants**

At first glance, solid propulsion may appear much simpler than liquid propulsion. The oxidiser and fuel are pre-mixed and poured into the tank, where they form a solid block in a predefined shape. This block, called grain, is burned off during flight, thus converting the
tank into a combustion chamber. A nozzle at the exit completes the solid-fuelled rocket motor. If desired, engineers can alter the grain's shape to increase or decrease the grain area to be burned off, thus modifying the amount of exhaust gas generated over time and therefore the thrust level.

The devil, however, is in the details. Very pure ingredients are required to get the propellants right, and mixing, casting and curing them is often referred to as 'black magic' among rocket scientists. Whether the propellant ends up sticking to the combustion chamber wall (as it should), for example, or whether it develops cracks, is almost impossible to predict, and is hard to get right. If this is not done correctly, the motor will explode, and it is difficult to determine the source of the failure (contrary to liquid-fuelled engines, a solid-fuelled motor is always spent after testing, even if the test is successful). The production processes employ more chemical engineering than mechanical engineering and are not as straightforward as calculating the loads and temperatures for a liquid-fuelled engine and then simply building it.

As with the liquid propellants, new developments in solid propellants have been sporadic over the past decades. Nowadays, only two basic types of solid propellants are used for rockets. One is the double-base propellant, which contains nitrocellulose and nitro-glycerine, and is only found in small, low-cost, short-range rockets due to poor performance (a low $I_p$). The other type is composite propellants, which use ammonium perchloride as an oxidiser, aluminium powder as fuel, some type of plastic as a binder (which is also burned off like the aluminium fuel) and some minor additives. Sometimes high explosives like hexogen (RDX) or octogen (HMX) are added to the mix. Alternatives to these components have been proposed for decades, one example being ammonium dinitramide (ADN) as an oxidiser, but so far none has fulfilled its promises, as higher performance came with significant drawbacks such as higher costs or reduced durability. Therefore, for decades now, only aluminium composites are found in high-performance solid-fuelled rocket motors, for space launchers as well as for ballistic missiles.

**Airframe**

The airframe is the dead mass that holds everything together. It also gives the rocket its aerodynamic shape. For liquid-fuelled rockets, the propellant tanks make up a considerable part of the airframe. Using the tank walls as a load-carrying part of the rocket's structure eliminates the need for two separate walls, thus reducing structural mass.

This philosophy of integrating as many functions as possible into a single structural part, and therefore saving weight, is consistent across rocket design. Another example is the common bulkhead between the oxidiser and propellant tanks, which may reduce weight, but increases the risks both during production and operation. As everywhere in rocketry, trade-offs need to be made.

For solid-fuelled rockets, the design of the main structural element, the tank/combustion chamber/load-carrier, is usually determined by its role as a combustion chamber; an effective combustion chamber will also be able to sustain structural loads during flight.

For any rocket, designers make great efforts to keep the airframe’s weight as low as possible. Every extra kilogram in weight carried by the missile translates either into a reduced payload mass, or into reduced range, thus undermining a missile’s two main objectives.
Aerodynamics, on the contrary, are a small consideration, especially for larger missiles. A larger missile’s shape is primarily dominated by manufacturing and weight considerations, and only to a lesser degree by aerodynamic considerations. The missile’s cross section should not be too big, but a very high length-to-diameter ratio would also have a significant effect on the weight of the airframe relative to the propellant mass, because more airframe material (for example, tank walls) is needed for the same amount of propellants if a rocket is longer and thinner. A length-to-diameter ratio of between ten and 15 is often used and seems to be a favourable trade-off.

**Navigation, guidance and control**

The guidance system can be seen as the ‘brain’ of a missile. It keeps the missile on its intended trajectory, steering it to the target. The guidance system also determines when the engine is cut off, thus also controlling the missile’s range.

A common misunderstanding regarding missile guidance is the belief that air-defence missiles and ballistic missiles operate similarly because both use guidance technology. However, the number of external inputs that are used in the two types of missiles differs significantly. A missile that is used to target aircraft must first lock onto its moving target and try to reach it as quickly as possible. While the missile’s speed and the moment of engine cut-off only play minor roles in a successful interception, permanent external inputs from its guidance system are essential as the missile must constantly track its target and adjust its trajectory accordingly to intercept it. For a surface-to-surface ballistic missile, however, the optimum trajectory can be calculated in advance because the target is stationary and the guidance system only needs to keep the missile on this trajectory. This means that a ballistic missile can usually fly to its target using its onboard acceleration sensors, without any external input. It is also almost impossible for an adversary to hack an incoming ballistic missile in flight – there simply is nothing to be hacked. In many ways, this makes a ballistic missile comparable with artillery, where a projectile is fired on a pre-calculated ballistic path toward a predetermined target location.

Historically, most ballistic missiles used gyros to check the system’s orientation and acceleration. Due to advances in electronics, small acceleration sensors and high-performance computers now fulfil this role in modern missiles. Data from these can be cross-checked with information acquired from onboard star trackers (celestial navigation), or even a GPS, but the bulk of guidance work conducted during the flight is handled by the missile’s internal guidance system. As this information is updated, the control system translates the guidance system’s commands into actual movement, using moveable engines, nozzles, jet vanes or other means to affect the missile’s orientation during flight.

Of course, payloads can function like air-defence missiles, by actively homing in on a target during the terminal phase of flight. But if the warhead or re-entry vehicle has the capability to change course, a complete guidance-and-control system with power supply must be added to the warhead. This increases the weight that has to be carried by the missile and takes up space. Both weight and space, of course, are at a premium.

**Payload, warhead and re-entry vehicle**

At this stage, a brief look at the payload itself is warranted. This leads to a minefield of different definitions and terms that are used by the expert community, including payload, warhead, weapon and re-entry vehicle. There are no clear definitions for these terms and they are frequently used interchangeably.

From an engineering perspective, what the missile carries on top is irrelevant, as long as the size, shape and weight of it fall within predefined limits. (The term ‘nuclear capable’ therefore makes absolutely no sense for ballistic missiles: if a nuclear weapon is small and light enough, it can be carried by any missile.) From

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**Figure 7: Payload, warhead and re-entry vehicle**

![Diagram](Source: Markus Schiller for IISS)
here on, it makes sense to define everything sitting on top of the delivery system as a ‘warhead’ (which can be separated). This includes multiple warheads, which can include separate re-entry vehicles. Inside these, the actual weapon can be found, for example a nuclear device (including all the wires, batteries and fail-safe devices), which in turn houses the weapon charge – the object that actually explodes or otherwise affects the target as intended (for example chemical agents).

**The missile system**

As previously mentioned, a missile alone is useless. To operate it, a complete missile system is required, including not only the actual weapon that is to be delivered to the target by the delivery system, but also launch and support systems.

**Launch and support systems**

Every missile must be launched from a dedicated launch platform. This platform can be stationary or mobile. Other necessary equipment includes systems that service the missile just before launch, for example by pressurising the tanks, spinning up the gyros, providing a power supply or feeding target information and trajectories to the guidance system or warhead. These systems can be integrated into the launch platform (for example into a submarine) or separate from the missile (for example in a building next to the launch pad) and connected by wires.

Additional support equipment and personnel may be needed too, for example for fuelling the missile prior to launch, for mating the warhead to the rocket, or to analyse meteorological conditions at the launch site that may affect the trajectory. The equipment needed for these tasks is referred to as support systems.

**TELs, silos and submarines**

A missile can be designed to be prepared for launch in advance, for example before it is lowered into a silo or a submarine, and held in a permanent ready-for-launch state once deployed, thus eliminating the need for the aforementioned support systems. Nonetheless, the silo or submarine requires launch systems.

The same is true for mobile missiles on ground vehicles. Transporter erector launchers (TELs) and mobile erector launchers (MELs) have to be equipped with all the required launch systems or they need separate vehicles close by to fulfil this role. The only difference between TELs and MELs is that the former consist of a single vehicle whereas the latter comprise a separate tractor and trailer. This means that TELs and MELs are much more than just trucks carrying missiles. Missiles may be presented at parades on simple trucks or trailers, but they cannot be launched by these vehicles.

**Missile flight and performance basics**

A typical ballistic missile accelerates its payload to a predetermined speed ($v_t$), at a predetermined point ($P_t$) (altitude and position), with a predetermined heading (elevation angle $\theta_t$ and direction). If done correctly, the payload carried by that missile will fly exactly to its predetermined target, like a golf hole-in-one. The
The ability of a ballistic missile to deliver a warhead accurately is largely determined by its speed ($V_t$), angle ($\theta_t$) and position ($P_t$) when thrust is terminated. The more precisely these three conditions are met, the more accurate the missile.

The missile body may stay attached to the payload throughout the trajectory, or the payload may be separated from the missile after engine cut-off. Separation is usually required for ranges beyond 500–700 kilometres to avoid problems at re-entry.

The further the payload has to fly, the higher the speed required at engine cut-off. It is also possible to adjust the elevation angle of the trajectory at cut-off, but evidently there is an optimum angle for maximum distance (which would be 45° for a flat Earth). Flatter or steeper angles yield different trajectories (which are known as ‘depressed’ and ‘lofted’ trajectories respectively), but also reduce the range for the same cut-off speed.

The missile could of course slowly burn all its fuel over the course of the whole flight. But in doing so, it would have to constantly fight against Earth’s gravity using propellants just to stay in the air and not fall to the ground. The longer the missile has to do this, the more extra propellants are needed. More propellants are in turn needed in order to carry these extra propellants, resulting in exponential growth. Keeping the missile’s boost phase short is an attractive design option because the missile needs fewer propellants, meaning that a given range can be covered with a smaller missile. Likewise, a missile’s range increases if the boost-phase duration is reduced. However, there is a limit: an infinitesimally short boost phase is nothing more than a gunshot, and no gun has an intercontinental range. The two main reasons for this are that the launch acceleration would destroy any payload and, more importantly, that the dense air on the ground would act like a wall for any projectile travelling at extreme speed, completely shattering the projectile and transforming it (and its payload) into a plasma cloud.

Short boost phases are therefore attractive, but there is a limit to what is achievable. High-thrust rocket engines/motors also pose technical difficulties and mass issues. The optimum trajectory, resulting from all these factors, is shown in Figure 9 above.

The duration of a missile’s boost phase is determined by onboard propellant mass and propellant mass flow into the engines, the latter of which also determines the engine’s (or motor’s) thrust level. Throttleable liquid-fuelled engines also exist, but these will not be covered.

Figure 8: Ballistic-missile flight sequence

Figure 9: Typical 1,000 km-missile flight

Figure 10: Velocity curve of a typical 1,000 km-missile flight
Most liquid-fuelled engines for ballistic missiles offer constant thrust (which nonetheless increases with the missile’s altitude), as do most solid-fuelled rocket motors (in a simplified way). Considering these factors, both the system’s speed and its level of acceleration increase during the boost phase because the missile becomes lighter as it burns its propellants. Therefore, while acceleration at launch may be just a little over 1 g (including the 1 g of Earth’s gravity that must be permanently counteracted), acceleration at engine cut-off may be around 10 g.

Acceleration peaks again on a negative scale once the warhead enters the dense layers of the Earth’s atmosphere. Because of high supersonic (Mach 3–5) or hypersonic (Mach 5+) re-entry speeds and the warhead’s steep angle of approach, the result is not dissimilar from running into a wall. The warhead continues to decelerate toward a constant speed value, comparable to what a skydiver experiences before opening the parachute. However, most warheads hit the ground long before that equilibrium is achieved.

Concept of range vs payload

The first important parameter is payload mass ($m_p$). A greater payload mass requires the missile to accelerate more mass, resulting in a lower cut-off speed ($v_{co}$) and thus shortening the maximum distance it can fly. Conversely, the distance the missile can travel increases if its payload is reduced. Given that a missile’s range strongly depends on its payload mass, a reference range for a given missile can only exist if its payload mass is clearly defined.

Making the missile bigger, and thus adding more propellants, will yield greater range or payload.

Mass ratios

The same effect comes into play for the missile’s own weight. If the airframe is heavy, it cannot carry as much payload to the same range as a missile with the same engines and propellant mass but a lighter airframe. Airframe weight has a significant effect on a missile’s performance. To simplify calculating this effect without having to work with the empty missile’s weight as a parameter, analysts can utilise the structural design factor ($k_{net}$) to better understand the missile’s performance. The structural design factor relates to the empty missile’s net mass ($m_{net}$) (consisting of its airframe, guidance and engine) and the mass of propellants ($m_{pr}$) that the missile carries along. The lower the structural design factor, the better the missile’s performance. However, this is very hard to determine solely through external observation. Missile designers certainly endeavour to make every missile as light as possible but, as many aerospace projects attest, designs tend to become...
heavier than initially expected as the project proceeds. If the designers themselves are almost always wrong about a missile’s projected mass, external analysts can hardly expect to make a more accurate assessment. The only way to arrive at sensible numbers is to ignore any detailed mass models (which are also used for aerospace design and tend to give very optimistic projections), and instead use known numbers from existing missiles and stages.

The analysis of missiles with Soviet storable-liquid-propellant technology, for example, can be simplified by looking at the average density ($\rho_{r,av}$) of these rockets – which is quite constant – independent of the rocket’s size and launch mass ($m_0$). With this, and with calculated propellant mass, it is possible to calculate the missile’s most likely structural design factor.

**Thrust and specific impulse**

Thrust and specific impulse have already been introduced. Looking at the performance basics, it should now make even more sense that engines with a high specific impulse are attractive options. With the same mass of propellants, a missile achieves higher thrust over the same boost-phase time, or a longer boost phase with the same thrust, thus achieving higher cut-off speed and therefore greater range. The fact that these are exponential effects has already been mentioned.

The famous ‘Tsiolkovsky Rocket Equation’ dictates the relations between achieved speed (in this case maximum change of velocity [$\Delta v$], which is a little different from cut-off speed [$v_{cut}$, but close enough]), available engine (with the mentioned exhaust velocity [$c$]), the missile’s weight at launch ($m_0$) and the missile’s final weight at engine cut-off ($m_f$).

$$\Delta v = c \ln \left( \frac{m_0}{m_f} \right)$$

**Staging**

At a certain point, the exponential increase in the size of the missile dictated by the Tsiolkovsky Rocket Equation becomes staggeringly high. Engineers therefore introduced the concept of staging (which means dividing a rocket into two or more sections, known as ‘stages’, which are discarded one by one during flight). A lot of propellants are used up at the beginning of flight, when the missile is heaviest and therefore requires high thrust. Once these propellants are exhausted, however, it is undesirable for the missile to continue carrying empty fuel tanks and heavy high-thrust engines that are no longer needed. By dividing propellant tanks and engines into two or more stages and shedding those that are no longer needed at predetermined points during flight, the missile is able to get rid of a significant amount of its net mass throughout the course of
the flight. As a result, the missile becomes significantly lighter during the mid-flight stage, and can use other, smaller engines, which are optimised for lighter masses and for operating in the vacuum of space. Using staging, the range and payload of a missile of a certain size can be significantly increased – or the size of a long-range missile can be significantly reduced.

Due to characteristics of typical solid and liquid propulsion, including differing structural designs and differences in the weight of the propellant and specific impulse, solid-fuelled missiles require staging at shorter ranges than liquid-fuelled missiles. While a 2,000 km range is easy to achieve with a single-stage liquid-fuelled system, a solid-fuelled system benefits significantly from a two-stage design. And while liquid-fuelled intercontinental ballistic missiles (ICBMs) usually have two stages, solid-fuelled ICBMs require three stages.13

**Accuracy**

Accuracy is a difficult issue for designers as well as analysts to estimate. It should be mentioned that although some manufacturers and states supply figures noting the system’s alleged accuracy – usually in the form of a circular error probable (CEP) – these statements may be exaggerated. The institutions that designed the missile in question, as well as the armed forces that intend on using it, have a vested interest in overstating the missile’s accuracy to increase the credibility of their forces. Aside from actual combat use, it can be difficult for external observers to figure out if test launches represent a truthful benchmark for a given system’s accuracy. Although test footage showing objects hitting a designated target may be genuine, analysts must also consider the possibility of those shots being staged or rehearsed multiple times prior to dissemination. Accuracy depends on several issues, detailed below.

**Engine cut-off**

First, the engine (or motor) of a missile has to be switched off very precisely once the missile reaches the necessary speed for its predetermined ballistic trajectory to travel to its target – as in the analogy of the golf ball flying into the hole. If the missile travels too quickly, it will overshoot the target; if it travels too slowly, it will impact short of its target. To illustrate the precision with which the engine must be switched off, consider that a missile with a 1,000 km-range accelerating with 10 g just before engine cut-off will add 98.1 m/s to its speed every second, or close to 1 m/s every 10 milliseconds. After engine cut-off, the missile will still fly for almost 500 seconds on a ballistic trajectory. However, if the engine were to shut down just 20 milliseconds late, the missile would travel 2 m/s more quickly than intended, adding up to 1,000 metres of additional range over 500 seconds and therefore overshooting the target by 1 km. As such, if there is no means for mid-course corrections or terminal guidance onboard the warhead, the missile requires an extremely precise cut-off of its final rocket stage, whether it is solid or liquid propelled.

**Other effects on accuracy**

Many other variables may affect accuracy, including positioning errors at launch; alignment errors; shear forces and gyro drift; deviation during re-entry due to shear winds; unconsidered atmospheric effects and conditions deviating from those predicted; miscalculated rocket weight; minor deviations in engine/motor performance; and many more that are too extensive to be detailed here.14

**Post-boost guidance and control**

Once the missile begins its ballistic trajectory – when engine cut-off of the last rocket stage occurs – the speed (and flight direction) of the missile might be corrected to increase its accuracy. However, evidently this cannot be done with the rocket’s main engine(s), which were already too inaccurate at cut-off.15 Another set of engines is therefore required. These engines can also be mounted on a bus system, called a post-boost vehicle (PBV), which separates from the missile body and releases the warhead (or several re-entry vehicles) once it has fine-tuned the ballistic trajectory. To do so, the PBV also needs propellant tanks and a guidance and control system, which add additional weight to the missile, thus reducing its available warhead mass (and volume) and range. The addition of a PBV also increases the complexity of the system and the missile’s potential risk of failure. It also increases the costs and time required to design and produce the missile; in rocketry, nothing is free.
**Terminal manoeuvre**

Another way to increase a missile’s accuracy is through manoeuvres during its terminal phase of flight. While this sounds like a simple option, there are considerable challenges associated with this type of manoeuvre. To successfully conduct them, the incoming missile/warhead/re-entry vehicle must know its and the target’s exact location and reduce the difference between them by as much as possible. Such a manoeuvre might be conducted through the guidance system and onboard computer relaying instructions to manoeuvrable external canards and fins, or by actively changing the position of the object’s centre of gravity by moving a weight inside the object, or by firing additional thrusters. Alternatively, a seeker can provide the warhead with terminal guidance which it may use to steer toward the target. While the former approach requires very accurate onboard guidance, potentially with external support, the latter requires sensors – for instance radar or electro-optical – that can detect the target from a significant distance despite the possibility of clouds, reflections and other phenomena that may affect them at re-entry. Another complicating factor for long-range missiles during the terminal phase of flight is their very high re-entry speeds, which reduce the time and radius of movement for a manoeuvring system. Additionally, the missile must carry the equipment that is necessary for terminal manoeuvres, including sensors, guidance systems, computers, power supplies, control systems with actuators, cables and mounts. This again increases the weight of the system, therefore limiting the available space and weight for the actual weapon payload.

A warhead which contains all of this equipment, which separates from the missile body, is called a manoeuvrable re-entry vehicle, or MaRV.

**Reliability**

Reliability also affects accuracy. For an external observer, a missile flight might look successful if it launches without any obvious complications. However, unless an observer is aware of the missile’s target, it is impossible to know if the launch is successful. A missile may launch without complications but fly in the opposite direction, missing its target by twice its range. Wartime conditions may further influence the reliability of a missile. While test campaigns allow for well-timed and choreographed launch preparations, during wartime missiles might need to be launched at very short notice, in unideal weather conditions and by exhausted and nervous launch crews. Considering this, the actual reliability of a missile system during wartime is likely to be lower than what is communicated by the missile’s designers or operators.

**Testing for development, qualification, crew training and ageing surveillance**

While a missile’s reliability can be increased by running detailed simulations to identify potential sources of failure, most launch failures result from unexpected complications with the individual missile components or human error, both of which cannot be easily accounted for in simulation exercises. Only actual launches can reveal these flaws. There are therefore no entirely successful test campaigns. Analysts should be wary of public claims to the contrary and consider the possibility of undisclosed testing.

Once a missile design is finalised, serial production for the system must be organised. The first serial-production missiles are tested again to assess whether the move from prototyping to serial production has been successful. Individual missiles are also launched over the course of serial production so that the designers can be certain there are no quality issues resulting in defective systems. During and following production, occasional tests are also used to assess the potential effects of ageing and to provide training opportunities for launch crews. It should be obvious that any real missile programme needs occasional test launches. If these are not observed, it means that either the missiles are simply not intended for actual use, or the numbers of systems available are extremely limited and cannot be replenished.

**Deployment modes**

Assessing a missile based on the presented mode of deployment is another rabbit hole for analysts. As noted earlier, any launch site, whether it is a fixed pad, a silo, a ballistic-missile submarine, a ship or a truck, requires launch systems to either be integrated into the site or located close by. Some preparations, such as fuelling,
require additional support systems, which must also be integrated into the site or launch platform, or positioned close by. A simple truck with a basic launch table cannot launch a real missile on its own.

Temperatures also play an important role in the deployment of actual weapon systems. As with any other piece of equipment, operators must be sure that the missile works in extreme temperatures. As some propellant combinations are temperature sensitive and hypergolic, some systems are not suited for unprotected road-mobile deployment. For instance, extreme cold might freeze the propellants and damage the piping, irreparably damaging the missile. External factors must also be considered by operators; driving over a deep pothole or colliding with an external object might result in a shock load and create a leak, which could damage or even potentially destroy the missile. A missile must also be designed to withstand the expected loads of the selected basing mode. If the system is expected to be transported on the back of an off-road truck, for instance, it will need to be more robust than if it is deployed in a secure submarine tube.

All these problems could be addressed to a certain degree by using missile canisters for road-mobile use, but this is only done with solid-fuelled missiles. Although liquid-fuelled missiles can be fuelled in advance, some operators choose not to do this for fear of rupturing propellant tanks.
The history of rockets has always been a history of proliferation. A brief look at the history of rocketry and ballistic missiles gives an idea of the spread of technology.

**The German legacy: liquid-fuelled missile systems**

Prior to and during the Second World War, Germany made substantial efforts to advance the theories of rocketry and to develop associated technologies including liquid-fuelled rocket-engine technologies and guidance systems. This resulted in the development of the V-2, the world’s first guided ballistic missile, which was used extensively in 1944 and 1945.

At the end of the Second World War, German hardware, personnel and explicit knowledge were seized by the governments of France, the Soviet Union, the United Kingdom and the United States, although there were significant differences in the quantity and quality of these expropriations, as well as differing reasons and applications for utilising this technology. The US soon limited the use of liquid-fuelled rocket technology to civilian space flights, while the USSR developed these technologies for both defence purposes and space technologies. The UK only invested very limited efforts into rocketry, while France applied more energy to the development of solid-fuelled missiles.

From these origins, the spread of technology can be traced across multiple decades and different regions. Nations have acquired experienced personnel, hardware and knowledge for their rocket programmes through various legitimate and illegitimate means. No state has independently developed ballistic missiles without some sort of tangible or intangible proliferation.

**Diffusion of solid-fuelled missile technology**

The origins of modern solid-fuelled rocket technologies can be traced to the United States’ rocket and missile programme. Although early activities regarding research into solid fuels began in the 1930s, it was not until the 1950s that significant progress was made in the field. Once this proficiency had been acquired, other...
states were able to master it as a result of the diffusion of space-flight technologies, as well as through fora such as international conferences, and the publication of scientific material. Over several decades, China, France, India, Russia and the US invested substantial efforts into advancing their solid-fuelled-missile programmes, and other countries subsequently benefitted from the ensuing proliferation of these technologies. Whilst it took pioneering states significant time and resources to establish successful solid-fuelled missile programmes, other countries with fewer resources also benefitted from their success. Some states that claim to have developed entirely indigenous programmes, for instance, are known to use solid-fuelled motors that utilise technologies and methods that are known to have originated in other countries.22 As with liquid-fuelled systems, the proliferation of solid-fuelled rocket technology has always been a difficult problem to tackle.
Chapter Three: Information: the Raw Material for Analysis

Reliable information is the foundation of every analysis. Two aspects should be kept in mind:

- Information that is used for analysis should always be checked for credibility. This is relevant for multiple reasons: all too often, analysts are unaware that established information might actually be incorrect. They should also be aware that information may have been tampered with, for example that photos may have been edited or events staged.

- Classified information is not necessarily better than open-source information. The reverse is sometimes true: due to its nature, an analyst usually has no way of checking the source of classified information, and therefore cannot judge its credibility. This is usually not an issue for open-source information as its origin should be clearer (even though, all too often, the source is not given – a problem which is explored in the following paragraphs).

Exploiting open-source information

While it is rare to find technical data about operational missile systems published in hard-copy format in the public domain before the 2000s, recent online publications offer a great wealth of data on both historic and modern systems. However, analysts frequently encounter problems with the quality of data. All too often, data is presented either without suitable sources, or without an explanation as to how the author arrived at their conclusion. Even if data appears to be properly sourced, following references to various websites and papers may lead to dead ends or loops where information on a source’s origin and validity is suspect.

A major problem with online platforms lies in well-designed pages that present detailed information on various missile systems, sometimes including drawings, but often without explaining that the data displayed is reconstructed or estimated. Sometimes the authors do not have a strong background in rocketry, resulting in data that does not match the criteria of consistency throughout all essential rocket parameters, as described in a later chapter. Furthermore, if real data is available and can be compared by analysts against online sources, it may be found that the data on the web platform was incorrect. Blindly trusting data from these platforms and using it for threat assessments is a trap that many analysts still fall into.

To avoid this, analysts must check every piece of data from the public domain for plausibility before using it for missile-system analysis. Defining and assigning confidence levels to each piece of data might help, for example ‘high’, ‘medium’ and ‘low’ levels of confidence. These confidence levels should then be kept in mind during analysis and evaluation.

Many different types of information can be found in the public domain and all types should be considered in one way or another to create a comprehensive, plausible and consistent assessment of a missile programme. This applies not only to data for technical analysis such as photos, videos, technical data, dimensions and drawings, as focused upon here, but also information about the programme itself, including its progress; the experience of the designers, institutions and state in rocket development; the amount of available manpower, funds and other resources; visible programme milestones (or the lack thereof); and the number and sequence of static tests, test flights and corresponding failure rates. Other information about national capabilities, including industrial capabilities, other high-tech programmes, defence-industrial links with other countries, along with political interests and the possible role of the examined missile programme should also be considered. Together these aspects can build a comprehensive picture of the missile programme under examination.

Ways to acquire information

Nowadays, there are many ways for analysts to acquire information on missile systems. Classified sources are no longer the exclusive sources of information, as
they were during the Second World War and the Cold War. Today, parades and test launches from isolated states such as North Korea or Iran are publicly broadcast. Sometimes, additional footage is made available as imagery is tweeted in real time by casual observers who stumble upon it long before intelligence agencies. Commercial satellite imagery also provides analysts with a means for tracking activities and constructions at remote sites anywhere in the world.

It is important to be able to distinguish between forged and real information. Pictures are photoshopped, videos are modified, mock-ups are presented and events are staged. However, this problem is not new, nor is it exclusive to open-source information. As already mentioned, classified information is usually not sourced, and its content is therefore very difficult for analysts to verify: was the rocket dimension measured by someone, or did someone tell it to someone else, who in turn might have delivered wrong data, intentionally or accidentally?

The best, and most reliable, source of information is therefore *in situ* inspection of actual hardware by an analyst. Everything else has to be taken with a pinch of salt. Obviously, the opportunities for *in situ* inspection are usually extremely limited. For this reason, it is very important for analysts to keep an overview of every aspect of a missile system, or even the entire programme. Wrong data from poor sources or purposefully misleading information can mean that certain aspects do not add up, affecting wider thinking. Multiple small mistakes can severely undermine missile analysis and eventually result in inaccurate analysis across an entire issue. The trick for analysts is to determine which parts of the puzzle are correct and separate those from assumptions and forgeries. Consistency and plausibility are key to substantial threat assessment.
Ballistic missiles are complex systems involving a massive number of parameters. However, they are still rockets and function according to the laws of physics. They can be described with equations and all their parameters are interrelated. While this characteristic makes designing high-performance rockets an extremely difficult task, it provides analysts who know how to read the hidden language of missile design with the tools to reconstruct a complete ballistic missile with only a handful of parameters.

**Primary aspects of technical missile analysis**

In principle, missile analysis is a reverse missile-design process. Starting with the visible results – missile size, visible features, perhaps some flight data – analysts can reconstruct an underlying mathematical model of the missile being examined and develop clear definitions of its key parameter values. While this is valuable in its own right, these values can also often allow analysts to identify possible lines of proliferation given the diffusion of missile technologies and technical knowledge.

This is a complex task which could be illustrated in detail over dozens of pages which would still barely scratch the surface; only a selection of relevant aspects for analysis can therefore be presented here. This will, however, give an idea of the potential that a technical missile analysis has to contribute to the debate.

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**Diameter**

A missile’s diameter (d) is a very important parameter when conducting technical missile analysis. Many analysts underestimate the efforts involved in production and are not aware that settling on a certain diameter for tanks, motors and airframes means setting up a precise production line. Given that even minor changes to the diameter of a missile would require the production line to be retooled, thereby wasting valuable resources and increasing risk, diameters are usually kept the same even if the missile is modified. Certain diameters may therefore hint at a missile’s origins and possibly even foreign support.

**Size**

A missile’s overall size is a frequently underestimated indicator of the missile’s range. Put simply, small missiles can only carry a limited amount of propellants and are therefore only able to cover short ranges. Conversely, larger missiles may cover long ranges. A simple weight estimation, assuming a cylinder with rocket length (l), missile diameter (d) and average density (ρ), yields a good estimate of a missile’s potential launch mass (m). Empty spaces in a rocket airframe still require load-carrying structures, which add unnecessary weight. They are therefore usually avoided, resulting in quite common average densities of roughly 1,200 kilograms per metre cubed (kg/m³) for solid-fuelled missiles and 850 kg/m³ for liquid-fuelled missiles.

**Number of stages**

Generally, analysts can use the number of stages of the missile as an estimate of the design’s range. Depending on the sophistication of the technology under examination, solid-fuelled missile designs may utilise two stages from ranges of around 1,000 kilometres. Solid-fuelled intercontinental ballistic missiles (ICBMs) usually feature three stages. Liquid-fuelled missiles can reach...
ranges beyond 3,000 km with just a single stage, while liquid-fuelled ICBMs usually require just two stages.

Minor visual details may help analysts to identify stage configurations. Cable connectors can provide helpful clues for the number of stages of a solid-fuelled missile, as these will never be located on solid-motor combustion chambers, but on top or below the chambers, thus hinting at the stage configuration.

**Stage sizes**

Identical stage sizes offer poor performance and hint at limitations in design and production. For two-stage designs, small upper stages (less than 20% of the total rocket) hint at dedicated space-launcher designs.

**Propulsion type**

There are only a few examples of rockets that utilise both solid-fuelled and liquid-fuelled stages. In these instances, the choice of design is driven by limitations in the availability of suitable engines or motors. Usually, a rocket design utilises either solid or liquid fuels across all stages. Since the number of available propellant combinations is quite limited, observed exhaust plumes can provide analysts with a clear indication of the propellants used, thus hinting at propulsion performance:

- Detached, smoke-free flame: double base (solid, low performance)
- Shining white flame with thick yellow/white smoke trail: aluminium composite (solid, high performance)
- Transparent, blueish, smoke-free flame: NTO/UDMH (liquid, high performance)
- Shining yellow/orange flame: inhibited redfuming nitric acid (IRFNA)/kerosene (liquid, low performance)

Details on the rocket itself can also provide analysts with hints about the propulsion type.
Liquid-fuelled rocket stages always have two clearly separated tanks for oxidiser and propellants, both of which require separate ports for filling, draining and venting. Areas surrounding fuel caps are sometimes colour coded to remind launch crews of the intended contents of these tanks. Historically, Soviet missile colour schemes used red for oxidiser and yellow for fuel. Indicating the influence of Soviet designs on their missile programmes, these colour schemes are still used on Iranian and North Korean liquid-fuelled systems. The location of filling ports for fuel and oxidiser along the back of the rocket can also provide analysts with hints as to whether the missile is fuelled vertically or not. These ports have to be accessible for ground crews, and when fuel and oxidiser ports are both located on the missile’s back end, this indicates that one of the propellant components can be pumped to the upper tank via riser pipe, meaning the missile is designed for fuelling once it is standing on the pad or launch table. This system means that hoses can be connected to the upright missile without crews needing to climb up ladders. If fuelling is done horizontally, therefore saving on the efforts and extra weight of adding a riser pipe to the missile, the fuelling port for the upper tank would be located on the upper tank.

Solid-fuelled rocket stages with solid-fuelled motors may consist of separate ring segments, but do not have vertical weld lines or any hatches or rivets along the combustion chamber. If these are visible along the main part of a rocket body, it is either a poor mock-up or a liquid-fuelled rocket stage, but not a solid-fuelled motor.

**Number of engines or nozzles**

Analysts should be aware that existing liquid-fuelled engines may be clustered together to generate greater thrust. Moreover, multiple combustion chambers with individual nozzles can be linked to a single turbopump. This process creates a multi-chamber engine with a higher thrust which is, counter-intuitively, easier to

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**Figure 20: Motor with one and four nozzles**

![Diagram showing a single nozzle motor and a four nozzle motor. Source: Markus Schiller for IISS](source_image_url)
handle than a single, larger engine. Clustering multiple available engines is a cheap and efficient alternative to developing new larger ones. Solid-fuelled motors may also use multiple smaller nozzles, which allow a shorter motor to be used. Designers might choose this option when designing missiles that will ultimately be stored in locations where space is at a premium, such as in submarine missile tubes or silos.

Visible separation planes, weld lines, rivets and hatches
Analysts should also take note of the separation planes that can be seen between the missile’s stages and at the base of the warhead. Parade mock-ups may lack these and they therefore provide a good indicator of whether or not a system is genuine. Rivet joints and hatches are also a useful indicator, as both must be located at sensible positions, for example, between or below propellant tanks. Rivet joints are never located on solid-fuelled motor combustion chambers, or on propellant tanks.

Being able to ascertain the difference between a mock-up and an actual missile also helpfully diminishes the possibility of the expert community assuming a state possesses a certain type of missile that otherwise cannot be verified.

Cable raceways
Cables, pipes and pressure lines never pass through solid-fuelled motor combustion chambers or liquid-propellant tanks. External raceways can therefore provide analysts with hints about the position and length of tanks or solid-fuelled motors.

Tank size
Propellant-tank sizes must correlate with the observed engines and the generated thrust and burn time. They must also correlate with the typical mixture ratio ($r_a$) of the assumed propellant combination.

Interstage design
This refers to the way in which two separate rocket stages are connected. Truss designs may hint at hot separation – when the upper stage is ignited while still
attached to the lower stage – which was favoured by some old Soviet design bureaus. To achieve hot separation, the exhaust gases of the upper stage blow through the truss design and explosive bolts are triggered, resulting in the lower stage being pushed away by the upper stage’s exhaust gases.

In turn, for liquid-fuelled missiles, cold separation requires small acceleration rocket motors at the upper stage that accelerate the stage at ignition, causing the liquid propellants to settle at the bottom of the rocket’s tanks.

**Fins**

The presence and location of fins can also provide analysts with clues about the missile’s likely guidance and staging. For instance, the presence of large fins at the back likely indicates that the missile under examination has an old guidance system that requires an aerodynamically stable rocket design. The presence of canards can hint at launch stabilisation or terminal guidance. Fins located in the middle of the body suggest that the missile will conduct low-altitude staging and has a small first-stage motor.

**Instrument section**

Large instrument sections are only required if a missile utilises an old guidance system. Most modern systems only have a small volume in the missile dedicated to this, so they have a small instrument section. An empty section may be added as a spacer above the instrument section to move the missile’s centre of gravity forward. This would be necessary if the weight of the warhead was reduced significantly below that of the missile’s original design.

**Submerged liquid-fuelled engines**

Some liquid-fuelled rocket engines are submerged in the propellant tank, leaving only a small portion of the nozzle visible. This approach adds a great deal of complexity and risk during design and production and is only undertaken when there are strict length restrictions, for instance for submarine-launched ballistic missiles. The presence of submerged engines may therefore provide analysts with helpful clues about a missile’s intended platform, especially if there is no other indication of its basing option. However, there are historical examples of submerged engines being used for land-based roles, for instance in North Korea’s Hwasong-10 (Musudan).

**Warhead**

Common designs for various missile types hint at a systematic missile programme. New warhead designs for comparable payload mass and range are not required. Very light warheads may require spacers to move the missile’s centre of gravity forward, very heavy warheads may require structural reinforcements on the missile body. Separable warheads must be aerodynamically stable at re-entry and can therefore provide hints about their interior design, which must be constructed with the warhead’s centre of gravity in mind. Shrouds may conceal the actual number and configuration of the warhead or re-entry vehicles.
Deployment mode
Road-mobile missiles need to be sturdy enough to withstand shocks and bumps during transportation, potential damage due to collision with external objects and the effects of extreme weather. Using nitrogen tetroxide (NTO) as an oxidiser may be a problem due to its very narrow operational temperature window, which renders it unsuitable for hot summer days and cold winter nights. Silo or submarine deployment on the contrary allow for very light and delicate airframes.

Control elements
Jet vanes create thrust losses due to friction, resulting in reduced engine thrust, but they are a simple and reliable option for thrust vector control. Other common options are steering engines or gimballed main engines.

Thrust termination vents
The final stage of a solid-fuelled rocket requires thrust-termination vents to ensure a very precise thrust cut-off when the payload enters its ballistic trajectory.

Performance data for reconstruction
Some performance parameters may be assessed with open-source resources, for example launch videos. For other parameters, official data has to be used, which may well deviate from actual values due to poor measurements or intended disinformation. The data points from all these parameters must be consistent with the reconstructed missile design. Performance parameters include:

Launch acceleration
Acceleration at launch may be measured if launch videos are available. The acceleration must be consistent with the reconstructed values for the missile’s engine thrust and launch weight.

Burn time
The burn time should be consistent with the reconstructed engine-mass flow and the available propellant mass.

Trajectory: range and altitude
The reconstructed missile model should match reported flight trajectories. If it does not, either the reconstruction or the reported flight data is incorrect.

Missile-testing patterns
Missile testing is a necessary requirement when the development of a missile system is under way. All aerospace companies utilise simulations partly for testing purposes, but simulations are only as good as the input parameters. ‘Unknown unknowns’ can cause unforeseen failures and can be difficult to factor into simulated testing. Establishing the reliability of a system is important given the stresses that wartime conditions might impose on the system and their crews, especially if missiles form an important element of a nation’s deterrence strategy and defence.

Testing patterns can therefore reveal much about the origins and the intended role of the system under examination. Analysts should be cautious when considering claims that a missile has supposedly been domestically produced if the system has a very limited test programme. Limited testing might indicate that the missile has already been extensively tested by another country and clandestinely imported. It might also indicate that the missile is not intended for actual use, and is being used for example as a stop-gap design.
**Ground tests**

Both liquid-fuelled and solid-fuelled rocket engines are usually fired for hundreds of tests on static test-stands before they are flown for the first time. Hundreds of engines have been developed over the past decades, and wherever test numbers are published and available, the same pattern of sustained static testing followed by flight testing is evident. There are some variations to this depending on the experience of the institution, as newcomers typically conduct more ground tests given the immaturity of their technology. Where there are significant exceptions to this pattern, analysts must consider the possibility that the system under examination has been imported from another country.31

**Flight tests**

Once the propulsion system has a proven track record of successful static tests, the first flight tests of missile prototypes may commence. Contrary to space launchers, missiles are typically produced in much greater numbers and subsequently stored. This means that serial production has to be established for missile systems. Doing so requires several milestones to be reached, each of which requires flight tests, to guarantee the reliability of the system:

- proof of concept: one or several tests
- development: several tests
- qualification/certification: several tests
- serial production set-up: several tests
- troop operational and readiness evaluations (Demonstration and Shakedown Operation [DASO] tests): one or several tests
- production-lot acceptance, ageing surveillance and troop training: continuous single tests over the years the system is in service

Considering this extensive testing programme, analysts should bear in mind that missile tests need to follow development schedules and not (for the most part) be subject to political whims or arbitrary dates. If engineers are instructed to test a missile on a certain date for political or propaganda purposes, the missile programme would need to be paused, with costs still running. As such, analysts should consider limited test numbers and tests on significant dates or occasions as indications that these ‘tests’ were not crucial to advance the programme. In such instances, it is likely that rigid test schedules are not necessary for the programme’s success. This may be because the programme either relies on proliferation from an external source or that it has a political rather than military application.

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**Figure 24: Common testing requirements**

Source: Markus Schiller for IISS
Chapter Five: Example of a Missile Assessment

The missile in question was launched during the 2006 Great Prophet 2 exercise in Iran. Three photos of the system are sufficient for a quick performance analysis.

The missile in question was apparently launched from a transporter erector launcher (TEL) based on the MAZ-543, a Soviet-designed vehicle that has been widely produced, exported and operated by former Soviet-bloc states. The dimensions of the MAZ-543 are well known, thus providing a benchmark and allowing the analyst to make initial estimates about the missile’s dimensions by means of comparison.

Knowing that the truck in Figure 25 (following page) has a width of 3.07 metres, the rocket’s diameter ($d_r$) is measured as 0.89 m. Once this is known, the rocket’s length ($l_r$) can also be ascertained, estimated here as 10.76 m. Due to the perspective of the image, the missile length is probably distorted, but not considerably – perhaps by around 2% – and can therefore be ignored.

Considering the guidance presented above, this section will present an exemplary analysis of a typical ballistic missile. This will provide a working example that analysts can replicate when conducting their own examination and assessment of missile systems.
Next, the propulsion type can be deduced. There is no contrail visible, and the yellow/orange exhaust flame with black streaks indicates a typical combination of kerosene and inhibited red-fuming nitric acid (IRFNA) with jet vanes: a standard Soviet storable liquid-fuelled missile configuration. There are also lines visible on the rocket body that indicate separated tanks, meaning that there is no common bulkhead.

According to Figure 14, 860 kilograms per metre cubed (kg/m³) is a typical value for the average density ($\rho_{r,av}$) of a missile with the observed liquid-fuelled technology. Simplifying the missile down to a cylinder with the measured dimensions, the launch mass ($m_0$) can be estimated as 5.76 tonnes (t).

The guidance compartment (section ‘G’ on Figure 26) is large, with a length of perhaps 0.85 m and a diameter of 0.89 m. This, combined with the large fins observable on the bottom of the rocket, indicates that the missile likely uses an old guidance system that requires aerodynamic stability during its ascent stage. Considering these parameters, we can infer that the missile was probably designed before the point in the mid-1960s when guidance technology significantly improved and negated the need for both components.

The visible separation lines between fuel tank (section ‘F’) and oxidiser tank (section ‘O’) provide indicators of the tank’s volume and, with that, the propellant mass. Assuming the designers used simple cylinders as tanks, the tank lengths ($l_t$) measure 1.64 m and 2.95 m, respectively. With the known propellant densities of 800 kg/m³ for kerosene and 1,570 kg/m³ for IRFNA, the resulting propellant masses are around 0.82 t of kerosene and 2.88 t of IRFNA. The resulting total propellant mass ($m_{pr}$) can therefore be calculated as 3.7 t.

Old missiles carry heavy warheads, and as stated above, the missile design points to an old missile. The size of the warhead also seems relatively large.
Therefore, as a working hypothesis, a warhead with payload mass \( m_p \) of 1 t is assumed for the missile. The empty mass with the warhead can therefore be estimated as 2.06 t and the net mass \( m_{\text{net}} \) as 1.06 t. With a 700 kg-warhead, the net mass would be 1.36 t.

The structural design factor \( k_{\text{net}} \) for the 1 t warhead would be 0.29, which is quite high but better than the resulting value of 0.37 for a 700 kg-warhead, which seems extraordinarily high. It therefore seems sensible to stick with the hypothesis of a 1 t-warhead, which results in a more realistic structural design factor.

From just these three images, it is clear that analysts can extract a significant amount of information about the system being examined. If additional data is available, such as a launch video, even more information can be extracted.

Having derived the length of the missile, the position relative to the ground can be measured for the first few seconds of the launch. With this, the average acceleration can be derived as 11.46 metres per second squared \( (\text{m/s}^2) \). Adding Earth’s standard gravity of 9.81 m/s\(^2\), the missile’s launch acceleration \( a_0 \) can be calculated as 21.27 m/s\(^2\), or 2.17 g.

With the calculated launch mass estimated to be 5.76 t, the thrust \( F \) at work can be calculated as 122.5 kilonewtons \( (\text{kN}) \). The previously identified jet vanes that disturb the exhaust gas flow out of the nozzle will reduce the engine’s effective launch thrust by a few per cent. Assuming 5% of losses, the actual thrust of the engine at launch \( F_0 \) is calculated as 128.6 kN.

Using these reconstruction results, a simple range calculation can be made. The result is that the missile has a nominal range of roughly 300 km when carrying a 1 t payload. This calculation can be made by looking up existing payload range diagrams,\(^{32}\) or by entering the known parameters into trajectory calculation tools, which usually requires some extra reconstruction work and educated guesses on other parameters, such as burn time, specific impulse and propellant residuals.

<table>
<thead>
<tr>
<th>Table 1: Reconstructed data and real data</th>
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<tbody>
<tr>
<td>Reconstructed</td>
</tr>
<tr>
<td>( \sigma ) [m]</td>
</tr>
<tr>
<td>( \lambda ) [m]</td>
</tr>
<tr>
<td>( m_0 ) [kg]</td>
</tr>
<tr>
<td>( m_{\text{net}} ) [kg]</td>
</tr>
<tr>
<td>( m_{\text{net},O} ) [kg]</td>
</tr>
<tr>
<td>( m_{\text{net},F} ) [kg]</td>
</tr>
<tr>
<td>( m_0 ) [kg]</td>
</tr>
<tr>
<td>( m_{\text{net}} ) [kg]</td>
</tr>
<tr>
<td>( k_{\text{net}} )</td>
</tr>
<tr>
<td>( F ) [kN]</td>
</tr>
</tbody>
</table>

Source: Markus Schiller for ISS
As more experienced missile analysts might realise, these numbers look familiar, as does the missile’s configuration, the reconstructed data and the pre-mid-1960s design. Comparing the reconstructed data with the nominal data of the original Soviet R-17/8k14/Scud B missile, analysts can conclude with high probability that Iran launched a Scud B during the Great Prophet 2 exercise. The analysed missile looks exactly like a Scud B, is launched from the same TEL and the reconstructed data values deviate only a few per cent from the Scud B’s known data.

This example illustrates that while missile reconstruction might be a black box for the inexperienced, it certainly is not black magic. Knowing what to look for and how to apply basic engineering principles can provide analysts with the right tools to reach surprisingly accurate results even when using a simplified approach.
Conclusion

In general, ballistic missiles are seen as a major threat, and rightly so. Like no other weapon system, missile systems can cover great distances, offer short launch and flight times, are hard to defend against and may cause massive damage (especially if armed with nuclear weapons). They are capable of projecting serious threat scenarios, from a regional to a global scale.

However, the myth that has surrounded ballistic missiles since their first use in the Second World War may be overblown. As this paper has tried to illustrate, missiles are not ‘black boxes’ with an arbitrary potential to project threats. While ‘rocket science’ is certainly involved, there is no magic required to analyse the performance and capabilities of missile systems. A sober analysis approach that strictly follows physical and mathematical principles, takes engineering realities into account and is complemented by experience will yield robust results.

If analysed accurately, ballistic missiles can be unmasked for what they are: not terror-inducing Wunderwaffen, but complex yet simple machines whose capabilities are frequently exaggerated. Whether they are used as political tools or as weapon systems, understanding them is essential – and possible, if analysts know what to look for.
Glossary

Airframe
The dead mass that holds the rocket’s other elements (propulsion, guidance and control system, warhead) together.

Ballistic missile
A missile that throws its payload on a ballistic trajectory toward the target, therefore using rocket propulsion to quickly accelerate to maximum speed. May enter space for longer distances.

Cruise missile
Missile that always stays within the Earth’s atmosphere. Uses air-breathing engines and significant aerodynamic lift throughout most of its trajectory.

Flight tests
Tests of rocket stages or whole rockets in flight.

Fuel
One of the two rocket propellants. Requires oxidiser to burn.

Guidance and control system
Keeps the rocket/missile on its intended trajectory. Consists of the guidance system (the rocket’s ‘brain’ that decides what to do) and the control system (which executes the guidance system’s commands).

Hypergolic propellants
A combination of fuel and oxidiser that react violently once they come into contact with each other, without requiring an ignition process.

Jet vanes
Rudder-like devices sticking into the hot rocket exhaust at the end of the rocket engine’s/motor’s nozzle, which can steer the rocket in a different direction when rotated, though only when the engine is on.

Launch mass ($m_0$)
Total mass of the rocket at the moment of engine ignition (at launch).

Liquid-fuelled engine
Propulsion unit for a liquid-fuelled rocket. Burns liquid fuel and oxidiser.

Liquid-fuelled rocket/missile
Rocket/missile that is powered by liquid-fuelled engines.

Manoeuvrable re-entry vehicle (MaRV)
Common term for a separable warhead that can execute manoeuvres within Earth’s atmosphere while it is closing in on its target.

Mobile erector launcher (MEL)
Tractor and trailer with specialised onboard equipment that can transport and launch missiles.

Multiple independent re-entry vehicle (MIRV)
Common term for a ballistic-missile payload that consists of more than one re-entry vehicle, and has the means to deploy each re-entry vehicle on a slightly different course, thus requiring a post-boost vehicle (PBV).
<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Net mass ($m_{\text{net}}$)</td>
<td>Mass of the empty rocket without payload and propellants.</td>
</tr>
<tr>
<td>Nozzle</td>
<td>Mounted at the back end of any rocket engine/motor. Required to accelerate the exhaust gas to high supersonic speed, thus creating thrust.</td>
</tr>
<tr>
<td>Oxidiser</td>
<td>One of the two rocket propellants. Reacts violently with the fuel.</td>
</tr>
<tr>
<td>Payload</td>
<td>Common term for anything that a rocket carries to an intended target, for example satellites to orbit for a space launcher, or one or more warheads for a ballistic missile.</td>
</tr>
<tr>
<td>Post-boost vehicle (PBV)</td>
<td>Platform with propulsion and guidance system, capable of navigating through space and deploying one or more re-entry vehicles on predetermined trajectories. Comparable to a satellite bus carrying warheads.</td>
</tr>
<tr>
<td>Propellant mass ($m_{\text{pr}}$)</td>
<td>Combined mass of oxidiser and fuel onboard the rocket.</td>
</tr>
<tr>
<td>Propulsion</td>
<td>Accelerates the rocket using liquid-fuelled rocket engines or solid-fuelled rocket motors.</td>
</tr>
<tr>
<td>Re-entry vehicle</td>
<td>Common term for an object that contains a weapon payload and is sufficiently protected by a heat shield to survive re-entry into Earth’s atmosphere and safely deliver the weapon payload to Earth. In some cases, this is equivalent to a warhead.</td>
</tr>
<tr>
<td>Solid-fuelled motor</td>
<td>Propulsion unit for a solid-fuelled rocket. Contains a solid propellant grain consisting of pre-mixed fuel and oxidiser.</td>
</tr>
<tr>
<td>Solid-fuelled rocket/missile</td>
<td>Rocket/missile that is powered by a solid-fuelled rocket motor.</td>
</tr>
<tr>
<td>Specific impulse ($I_{\text{sp}}$)</td>
<td>Rocket parameter that defines the efficiency of the rocket’s propulsion in converting propellants into thrust.</td>
</tr>
<tr>
<td>Static tests</td>
<td>Tests of engines, motors or complete rocket stages that are fixed to the ground.</td>
</tr>
<tr>
<td>Transporter erector launcher (TEL)</td>
<td>Special vehicle with specialised onboard equipment that can transport and launch missiles.</td>
</tr>
<tr>
<td>Warhead</td>
<td>Common term for a missile’s payload, intended to inflict damage at the target. May contain several types of weapons, for example nuclear weapons, chemical agents or high explosives.</td>
</tr>
</tbody>
</table>
Notes

1 Hybrid rocket motors combine solid and liquid propellants. While often promoted as combining the best of two worlds, critics claim the opposite. The fact that no ballistic missile has ever used hybrid propulsion indicates that the latter may be true, at least for weapon systems.

2 While there are countless combinations of chemical compounds that react violently, they must meet certain criteria to be considered suitable for rocket fuel. The compounds must have a very high energy density, meaning that they can release vast amounts of energy for their weight. They should do this in a way that can be controlled, for example with combustion stability in the engine and without exploding on their way to the engine or in the tanks. Furthermore, the total density of the compounds should be high, meaning that the ratio of storage space and stored energy should be sensible, as bigger tanks weigh more. The compounds should also be liquid at reasonable temperatures. When other issues, such as the fuel’s behaviour as a cooling fluid, its viscosity, ageing, corrosiveness, availability and cost, are taken into account, there are only a few propellants that are suitable for high-performance missiles.

3 There are exceptions to the rule. The Scud A, for example, used pressurised tanks. However, because of the weight of these, the missile only had a 170 km-range, whereas its successor, the Scud B, could travel up to 300 km with a turbo-pump engine.


5 Although a solid-fuelled motor can be designed to be reused, meaning that another grain can be inserted and the motor fired again, the new grain carries risks like cracks and fissures or limited case-bonding. The material properties of the motor case and nozzle might have also changed in a way that could affect the motor’s behavior if fired again. After a solid-fuelled motor is fired successfully, it can therefore actually only be stated that it would have worked.

6 Designers use lightweight materials; implement smart design solutions; combine the functions of various parts into a single part; reduce safety factors; stick as closely as possible to material limits (thus reducing weight, but increasing risk); and much more. Just like a Formula One race car could be built to reach the finish line at every race but weigh too much to win any race, rocketry is a trade-off between risk and performance.

7 These external inputs serve as the eyes and ears of the operation. The missile needs an onboard radar or infrared/optical sensors to look out for the moving target and act accordingly to intercept it.

8 Interceptor missiles may receive updated information from ground-based long-range sensors about their target’s position, as well as their own position, during flight, until they are close enough to lock onto their target by themselves. From then on, the interceptor has to use its own sensors to receive updated information on the target’s position and movement.

9 Target information can still be updated at any time. Missiles that are ready-for-launch have to be fuelled in advance, which usually reduces their lifetime slightly. Once fuelled, the Scud B still had a shelf life of 12 months, which could be extended once the missile was drained and cleaned. Other missiles (liquid- and solid-fuelled) can sit in their silos for well over a decade.


11 Other external factors also affect a missile’s range. The same missile with the same payload mass will fly further if launched straight eastward (the closer to the equator, the greater the effect), from high altitudes (for example highlands) or at high temperatures. The terms ‘reference range’ and ‘nominal range’ therefore only make sense if the actual launch conditions are agreed upon – which they are not. Usually, experts do not even agree on the reference payload mass of an analysed missile. Therefore, postulated range numbers always have to be taken with a large pinch of salt, even before accounting for mistakes in the calculations.

12 In the equation, ‘ln’ refers to the natural logarithm function. The natural logarithm of a number is its logarithm to the base of the mathematical constant e.

13 Every operational ICBM has an additional post-boost system (PBS), powered by small liquid-fuelled engines, for precise trajectory injection, which also allows re-entry vehicles to be placed on different trajectories and therefore to hit different targets. The PBS is sometimes incorrectly counted as an extra stage.
For further reading, see R. Schmucker and M. Schiller, *Raketenbedrohung 2.0*, (Hamburg/Berlin/Bonn: Mittler Verlag, 2015), chapter 3.6.

Main engine thrust is designed for rocket ascent. By this point, the rocket is empty and very light. Using high thrust for corrections would be like using a sledgehammer for detailed sculpting.

This actually happened during the Scud B’s first launch for the official joint flight-test campaign on 25 August 1960.

Such complications may include wrongly connected cables, items left at critical locations at or within the rocket and many other failures.

Single successful launches may indicate a significant use of previously tested hardware components. In some cases, single successful launches may also be lucky shots, just like maiden flights of space launchers sometimes actually work. However, actual development requires many test launches and launch failures must be expected for any real missile development programme.

This also means that many more missiles have to be produced than are actually deployed, because at each test launch, a missile is used and lost. For example, the Soviet Union reportedly deployed 544 SS-N-6 submarine-launched ballistic missiles and tested 653, meaning that more than twice the number of deployed missiles had to be produced. The US Trident II D5 missile has been tested almost 200 times by now, and up to 24 missiles are deployed onboard each of the 14 Ohio-class submarines (not counting the four British Vanguard submarines).

This was the case for the Saudi Arabian DF-3A missiles. They were procured from China, so did not require further tests relating to development and production in Saudi Arabia and, since a missile is gone once it is launched, no missiles were ever launched for crew training.

This is simply a result of limited resources. It saves considerable resources to look and absorb what others have already achieved.

The Pakistani solid-fuelled motor programme, for example, seems to be completely based on the Chinese programme.

Data was rarely published and if it was, the journals, books or other publications containing it were hard to find.

Real data may be available from handbooks, actual hardware (for example missile debris), conversations with involved designers or operators, or other classified sources.


Changing the value of a very minor parameter at one end of the rocket can send massive ripples through the whole system, leading to significantly different values. In most cases, changing one parameter in a ‘positive’ way affects ten other parameters in a ‘negative’ way. Missile design is an art of balancing out parameters. It is an endless task of optimisation while trying not to destroy the design.

The famous Scud’s diameter of 0.88 m dates back to the failed Soviet R-101 adaptation of the German Wasserfall air-defence missile from the Second World War. The modern Iranian Qiam also has the same diameter. Diameters for many engineering products, for example airliners, remain the same. Once a basic aircraft is developed, longer or shorter versions will soon follow but all with the same diameter.

Solid- and liquid-fuelled designs are very different, requiring completely different manufacturing technologies, testing equipment, design philosophies, infrastructure and more. Usually, multi-stage missiles are designed by one team, which opts for one technology, and then produced on one site.

Large kerosene or hydrazine engines may suffer from combustion oscillations, a problem that is hard to resolve on a newly designed engine.

Mock-ups may be made by simply welding a steel cone on a steel cylinder and therefore often do not have a typical separation plane.

North Korea is known to have tested its latest large rocket engine only twice, in September 2016 in single-engine configuration and in March 2018 in 1+4-configuration (main engine and four verniers). The double-chamber configuration flown in the Hwasong-15 in November 2017 was never tested. Even assuming that a handful of tests might have taken place in secret, hundreds of tests would have been required for indigenous engine development. It should therefore be clear that proliferation was involved in this case.

See for example R. Schnucker and M. Schiller, *Raketenbedrohung 2.0*, p. 108.

This data is widely available. One reliable source is the original documents and notes of former officers of the East German National People’s Army, which had R-17/Scud B systems deployed until unification with West Germany in 1990.