Beyond the 2000 km range limit, Iranian IRBMs

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ABSTRACT

Iran officially limits the range of its ballistic missiles to 2000 km. However, Iran claims that its Khorramshahr missile can achieve this with a 1500-1800 kg payload. This implies that, with a reduced payload, its range could exceed the 3000 km threshold to be classified as an IRBM. Furthermore, in April 2020, Iran launched the Qased Satellite Launch Vehicle. Based on publicly available information and analysis of photographs and video material, parameters of both missiles have been derived. These are used in trajectory simulations. Results show that the Khorramshahr's claimed performance is theoretically possible and it could be an IRBM. However, such a theoretical design is inconsistent with the missile displayed by Iran. The performance demonstrated by the Qased indicates that, if used as a ballistic missile, its range could exceed 3000 km.[ii]

INTRODUCTION

Based on public statements by officials, the range of Iran's ballistic missiles is limited to 2000 km. For instance, in a May 2017 interview, major-general Mohammad Ali Jafari said: 'There is the capability to increase this range, but it is sufficient for now as the Americans are present within a 2000 km radius around the country, and would get a response in the case of any invasion' [1]. At the time he was the commander of the Islamic Revolutionary Guard Corps (IRGC), the organisation responsible for the development and deployment of Iran's ballistic missiles. The 2000 km range would not only cover American bases in the region, but also Saudi Arabia and Israel, the stated foes of the Iranian regime [2]. Most of Europe would be out of range. A mere month later, however, brigadier-general Hossein Salami, then the IRGC deputy commander (since promoted to major-general and currently serving as the IRGC commander) said in an interview: 'If we have kept the range of our missiles to 2,000 kilometres, it's not due to lack of technology. (...) We are following a strategic doctrine (...) So far we have felt that Europe is not a threat, so we did not increase the range of our missiles. But if Europe wants to turn into a threat, we will increase the range of our missiles' [3]. Ballistic missiles that are currently in Iranian service are not known to have ranges that exceed 2000 km. For instance, the longest-range variant of the Shahab-3 missile has a stated range of 1950 km with a 750-800 kg payload [4] and the reported range of the solid-propellant Sejil is 2000 km [5]. However, Iran has flown a number of missiles with the potential to achieve longer ranges.

In September 2017 the Khorramshahr missile was unveiled, during a parade in Tehran, and video footage was released of it being launched. The first flight reportedly took place in January of 2017, with the missile failing after flying 600 miles. Contemporary news reports speculated that the missile is an Iranian version of the North Korean Hwasong-10, usually referred to as the BM-25 [6].

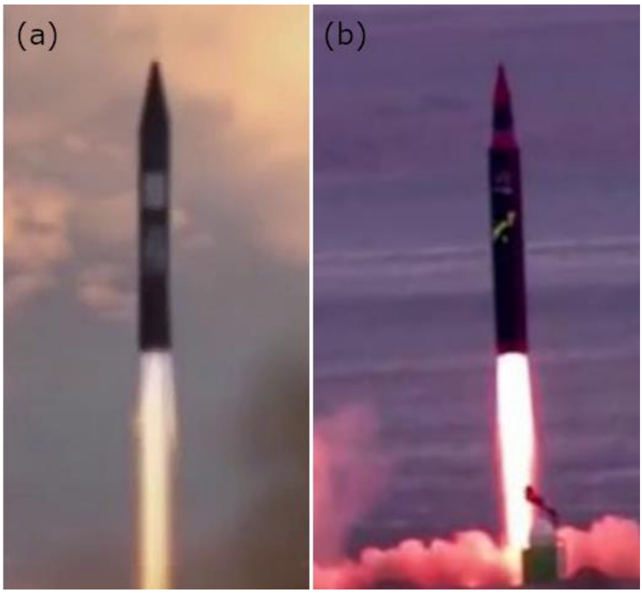

Figure 1: Video still of the Khorramshahr launch footage released in 2017 (a) and in August 2020 (b). (Original footage: PressTV and FARS News Agency)

The Hwasong-10 seems to use an 4D10 rocket engine, which originally powered the Soviet R-27 'Zyb' / SS-N-6 'Serb' [7]. This burns a combination of UDMH (unsymmetrical dimethyl hydrazine) and N_2O_4

(dinitrogen tetroxide), which is more energetic than kerosene and IFRNA (Inhibited Fuming Red Nitric Acid) used in most of Iran's other liquid-propellant ballistic missiles, such as the Shahab-3 or Ghadr-F/H. A disadvantage of this propellant combination is the limited temperature range in which the oxidizer is liquid, which poses problems for a missile that is supposedly road-mobile [8]. In September of 2019, a version of the Khorramshahr was paraded through Tehran with a smaller re-entry vehicle and in August of 2020 new footage was released of a test launch of such a missile [9, 10]. Screenshots are shown in Figure 1. The Khorramshahr's performance is unknown, but Iran claims it has a range of 2000 km with a payload of 1500 to 1800 kg and a take-off mass of 19,500 kg [11]. Potentially this may allow the missile to fly more than 3000 km with a reduced payload, which would make it an IRBM.

Iran's development of satellite launch vehicles (SLVs) may provide an alternative path towards ballistic missiles with longer ranges. A booster optimized for launching satellites differs from a ballistic missile intended to deliver a warhead to a ground target, but much of the technology is similar. Iran first orbited a micro-satellite using an indigenously developed launch vehicle in 2009, with its Safir SLV. The larger Simorgh SLV was unveiled in 2010.

Figure 2: The Qased satellite launch vehicle before launch. (Image: Reuters)

On the 22nd of April 2020 Iran launched the Noor satellite, using a previously unknown Satellite Launch Vehicle (SLV) called the Qased [12]. The US Space Force confirmed that Noor reached orbit, together with a second object, assessed as the spent upper stage [13]. The Qased is smaller than the Safir and Simorgh and was transported and erected using a trailer practically identical to those used for Shahab-3 variants, shown in Figure 2. The trailer's obvious modification removes a bracket, because the Qased is longer than a regular Shahab-3. The Safir and Qased use storable liquid propellants for their first stage (all stages for the Safir). Like the Khorramshahr, the upper stages of the Safir and Simorgh use N_2O_4 oxidizer, which constrains storage and operation environments. The Qased second stage appears to use a solid-propellant motor.

The Safir and Simorgh SLVs were developed under Iran's (nominally) civilian space agency. However, the Qased, like the Shahab-3 that it is derived from, is the responsibility of Iran's IRGC, linking it to Iran's military ballistic missile program. This raises the question how the Qased could perform if it were restored to its roots as a ballistic missile. According to another analysis, its range could be 2200 km with a 750-1000 kg payload [14].

We assess the performance of these missiles using numerical simulations. Parameters of the missiles for the simulations are derived from known properties of their engines and size measurements, based on analysis of open-source imagery. The approach for both missiles differs. For the Khorramshahr we try to answer the question whether, given the properties of a 4D10 engine, the claimed performance is plausible and whether such a missile can indeed deliver a substantial payload to more than 3000 km. For the Qased, parameters of its trajectory to orbit are known from open sources, including an Iranian video, and properties for its first-stage engine are known. The unknown parameters can be tuned such that the simulation results in the correct satellite orbit. Based on the found parameters, we check whether a hypothetical ballistic missile variant can exceed 3000 km if used on sub-orbital trajectories.

SIMULATION MODEL

The missile trajectories are simulated using a point-mass model, in which the three degree of freedom (3-DOF) equations of motion are integrated numerically, in Earth Centred Earth Fixed coordinates. The properties of the missile in the model are defined by the burn time, usable propellant volume, burnout mass, propellant specific impulse (at Sea level and in vacuum) and the cross-sectional area, for each stage, and the payload mass. This medium-fidelity model has been described in previous publications [8, 15]. For simulating SLVs such as the Qased, the model has been modified to calculate a pitch program for trajectories to orbit. The approach involves directing the thrust such that the missile follows a series of pre-

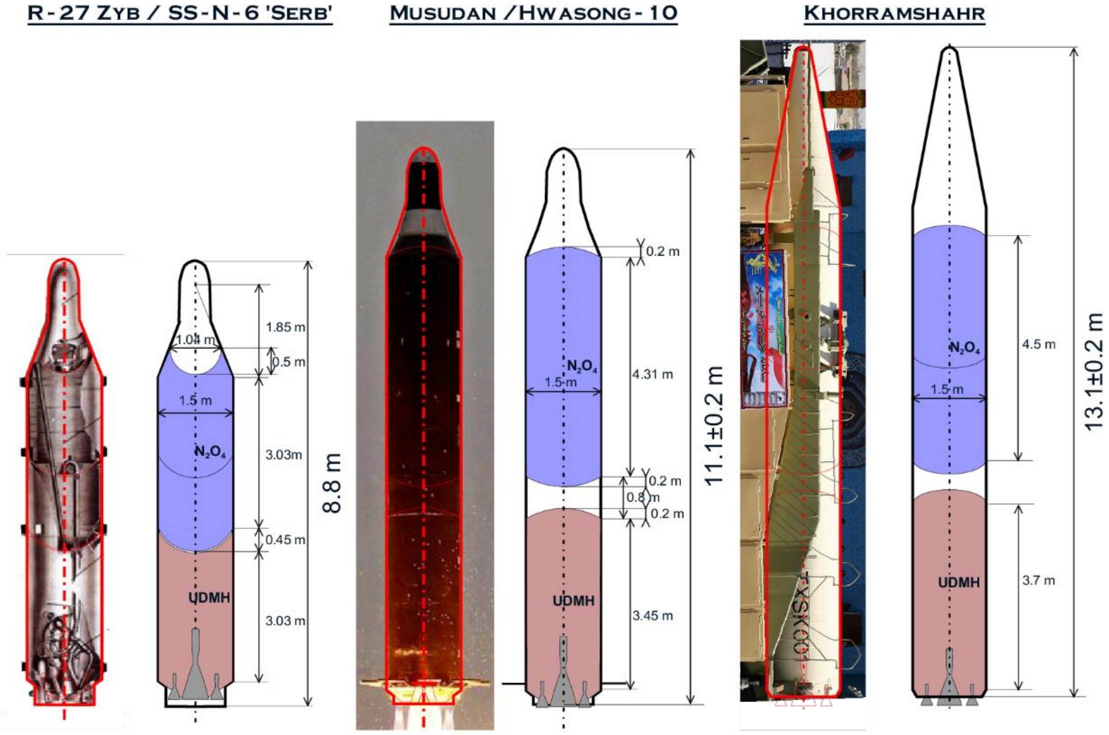

Figure 3: The Khorramshahr compared to the Soviet R-27 and North Korean Hwasong-10. Missiles shown to scale.

set constant pitch-rates, see e.g. [16]. The program iteratively changes these rates such that the satellite achieves either a circular orbit or, alternatively, an orbit with a prescribed apogee and perigee. The model was validated using publicly available information for trajectories of missiles with known parameters (the Atlas-F ICBM for sub-orbital trajectories and the US Minotaur I and the Chinese LM-3A for trajectories to orbit).

KHORRAMSHAHR

North Korea first showed their Hwasong-10 missile during a parade in Pyongyang in 2010. Superficially this missile was similar to the Soviet R-27. The Hwasong-10 was first successfully launched in June of 2016, when this similarity was confirmed: its engine is closely related to the 4D10 engine of the R-27, with N_2O_4 and UDMH as its propellant and two Vernier engines for steering. The R-27 was a single-stage missile with a 14,200 kg take-off mass, including a 650 kg payload, and a maximum range of 2500 km [7]. An analysis of the Hwasong-10's test flight confirms that its performance is consistent with the use of the 4D10 engine [8]. There are a few noteworthy differences between the two missiles, however. The R-27 was optimised to fit inside the diameter of Soviet 'Yankee'-class ballistic missile submarines. To reduce the length and structural mass of the missile, its oxidizer and fuel tanks had a shared bulkhead. Its guidance systems was located in a small compartment at the top of the upper propellant tank. Images of the Hwasong-10 show that it has longer tanks and has an inter-tank section between the oxidizer and fuel tanks, with separate bulkheads. The Hwasong-10 also has grid fins to stabilise the missile [7].

When Iran paraded the Khorramshahr through Tehran, in 2017, the missile's size was not immediately obvious. Images of the missile being displayed in Tehran in 2019, however, confirm that it shares the 1.5 m body diameter of the R-27 and the Hwasong-10. Images of the engine confirm that its configuration matches the 4D10. Scaling the dimensions in an image of the missile taken during the 2017 parade with this diameter results in an overall length of 13.1±0.2 m. This makes the Khorramshahr considerably larger than both the R-27 and the Hwasong-10, see Figure 3. The missile exhibited in 2019, see Figure 4, showed that, like the Hwasong-10, the Khorramshahr has an inter-tank section between the oxidizer and fuel tanks. Its oxidizer tank is split in two sections. Since the propellant tanks drain from top to bottom, the centre of gravity moves aft during the engine burn. Draining the lower oxidizer tank first is intended to keep the centre of gravity forward of the centre of pressure, thus stabilising the missile. Unlike the Hwasong-10, the Khorramshahr does not have grid fins. Its guidance equipment is housed in separate compartment above the tanks. Another difference is the payload section. The Musudan carries a single tri-conic re-entry vehicle. The Khorramshahr has a payload cover instead, with an unknown payload underneath.

According to Iranian press reports, the missile can carry multiple re-entry vehicles (e.g. [17]).

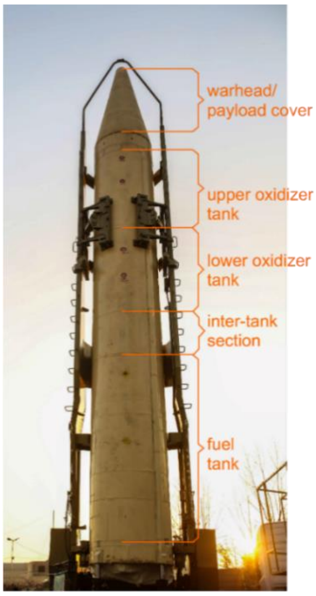

Figure 4: A Khorramshahr on display in Tehran in 2019 with major components indicated. (original image: DefaPress.ir)

Since the Khorramshahr's first flight reportedly failed and there is very little information on its subsequent flight(s), we do not have flight data to compare our models to. However, we can verify whether a missile with the claimed 19,500 kg take-off mass and a 4D10 engine can indeed fly the claimed 2000 km, assuming that the take-off mass includes a 1500 kg payload.

Table 1: Data for the two different 4D10 engine models used in the simulations

	Model 1	Model 2
thrust [kN] (sea level)	265	265
I_{sp} [s] (sea level)	265	270
I_{sp} [s] (vacuum)	290	299
propellant mass flow rate [kg/s]	101.9	99.6

There is some uncertainty in the performance figures of the 4D10 engine. Therefore, in our simulations, two different engine models were used, with the same thrust, but with a slightly smaller specific impulse for Model 1 [18] than for Model 2 [7] and consequently a slightly higher propellant mass flow rate. Details are listed in Table 1.

The remaining unknowns for the missile model are how much of the missile take-off mass is taken up by the useable propellant mass and, directly associated with this, the missile's burn time. The parameter we use to define these is the booster deadweight mass fraction, i.e. the mass of the booster at burnout as a percentage of the booster take-off mass. A smaller deadweight fraction means that more of the missile's take-off mass is taken up by propellant and therefore less by unused propellant and the missile's airframe, engine and guidance equipment. A smaller deadweight fraction makes the booster more efficient. By calculating the range as a function of the deadweight mass fraction, with a fixed take-off mass and payload, we can find the deadweight mass fraction for which the missile has the claimed performance.

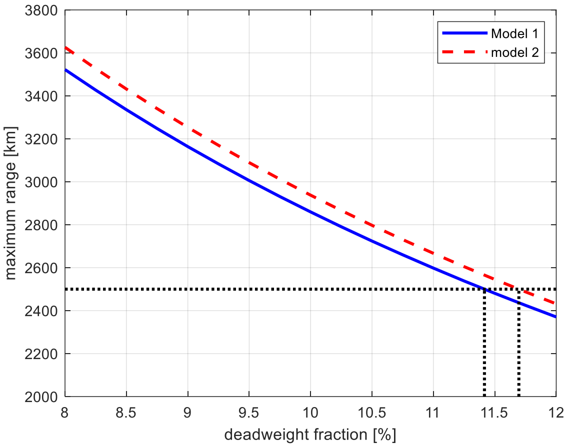

Figure 5: Range as a function of the deadweight mass fraction for the R-27, with two different engine models.

Figure 5 shows simulation results of the R-27, with both engine models. Its 2500 km range requires deadweight fractions of 11.4 and 11.7 percent for engine models 1 and 2, respectively.

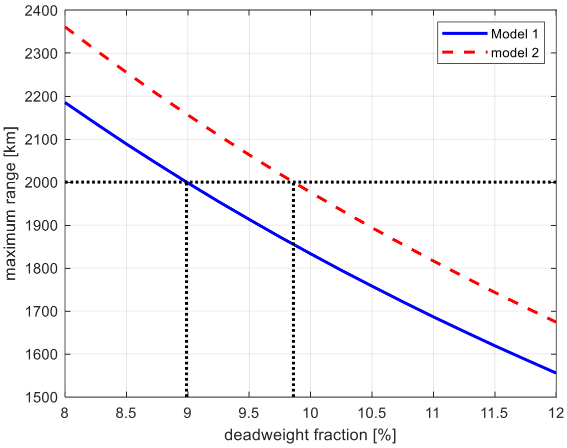

Figure 6: Range as a function of the deadweight mass fraction for the Khorramshahr with the two different engine models and a 1500 kg payload.

Figure 6 shows the result of similar simulations for the Khorramshahr, with a 19,500 kg take-off mass including 1500 kg of payload. The results show that, theoretically, this missile can indeed fly 2000 km (with both engine models). The required deadweight fractions and the associated propellant masses and burn times for this are listed in Table 2.

Table 2: Parameters for the claimed Khorramshahr 2000 km range with a 1500 kg payload, for two engine models.

	Model 1	Model 2
booster deadweight mass fraction [%]	8.99	9.86
burn time [s]	160.7	162.9
useful propellant mass [kg]	16382	16225

Based on the reconstruction of the Khorramshahr shown in Figure 3, the volume of the propellant tanks is sufficient to house the required propellant mass, but the required deadweight fractions are considerably smaller than those for the 'baseline' R-27. However, assuming the missile indeed has such a low deadweight fraction, we can calculate what its range would be with a reduced payload.

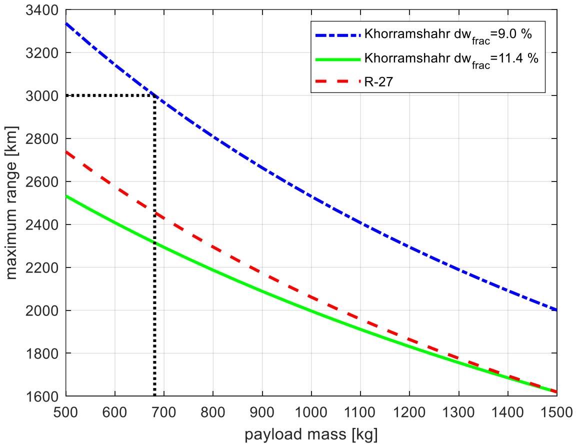

Figure 7: Simulated maximum range as a function of payload mass for the Khorramshahr with two different deadweight fractions and the baseline R-27 (with engine model 1).

The simulated range as a function of the payload is shown in Figure 7, for engine model 1 (results for model 2 are similar). Based on these simulations, the theoretical missile indeed is capable of flying more than 3000 km with a significant payload of more than 650 kg. The figure also shows the performance of the R-27 and a hypothetical Khorramshahr with the same deadweight fraction as the R-27. These results are a testament to the optimisation of the original Soviet missile, because they show that increasing the overall take-off mass and the propellant volume does not lead to an increased maximum range, unless the deadweight fraction is reduced.

Figure 8 shows an acceleration measurement derived from the launch video published in 2017. The time is scaled using the video frame rate and the altitude above the launch pad is scaled using the missile length.

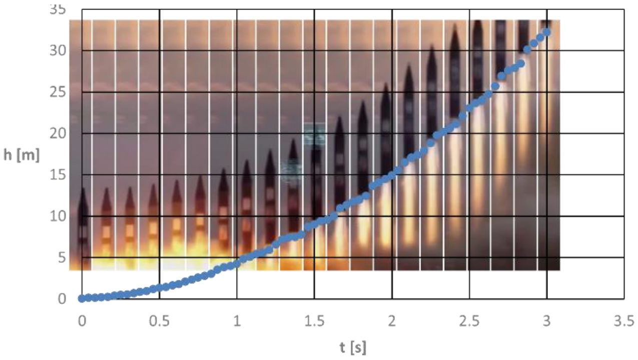

Figure 8: Position as a function of time for the Khorramshahr in its launch video, with one in five frames shown (original video: PressTV).

A second-order polynomial fit to the measurements gives a launch acceleration of 6.4±0.2 m/s^2. With a thrust of 265 kN for the 4D10 engine, this points towards a missile take-off mass of 16.3 tons, which is significantly smaller than the claimed 19,500 kg. Perhaps the video frame rate has been manipulated, but it is also possible that, for its first flight, the missile was flown with a reduced propellant load. Since the Khorramshahr lacks the Musudan's grid fins, it is conceivable that stabilising the missile required leaving the bottom oxidizer tank partially empty.

QASED

Much more is known about the flight of the Qased than about the Khorramshahr. The Noor satellite has been observed in orbit, with reported 444 km apogee and 426 km perigee altitudes and a 59.8° inclination (see e.g. [19]).

Figure 9: Screens from inside a ground station showing a graph of the total impulse as a function of time (inset a) and trajectory parameters at 392.3s after launch (inset b). (Original video still via Iranmedia.org)

Iranian media published video material of the launch, including footage taken inside a launch control centre. A screenshot is shown in Figure 9. Two of the screens, corrected for perspective and enlarged in insets (a) and (b), provide crucial information for finding parameters for modelling the missile. Inset (a) shows the total impulse as a function of time. It indicates that the missile has three stages and that, after burnout of each of the first two, the missile has coast phases, during which the engines do not burn. Linear interpolation using the time axis allows finding the burn times and the duration of the coast phases. Inset (b) shows trajectory parameters at 392.3 s into the flight. These include the velocity, altitude and the apogee and perigee altitudes of the then-current trajectory. Because the missile had not yet achieved orbital velocity, the latter is negative.

The coast phases may be significant. Launching a satellite to more-or-less circular orbit requires that, at burnout, the booster flies approximately parallel to the surface of the Earth at the velocity required to achieve orbit at its altitude, approximately 7.8 km/s for low-Earth orbit. This typically requires an upper stage or upper stages with relatively low thrust and long burn times. In contrast, the velocity at burnout for an IRBM on a 3000 km minimum-energy trajectory is approximately 4.8 km/s at an angle of roughly 40 degrees relative to horizontal. To limit gravity-loss, ballistic missiles tend to have short burn times and higher-thrust upper stages. It would be unusual for Iran to develop a ballistic missile from an SLV, but there are many historical examples of ICBMs being adopted as SLVs. To compensate for the relatively high thrust of their upper stage(s), it is not unusual for them to have a coast phase. This applies to the American Minotaur I, for instance, which was derived from the Minuteman ICBM. The coast phases in the Qased's flight profile suggest that its 2nd stage engine, in particular, has a higher thrust than is optimal for an SLV.

Like the Safir SLV, the Qased's first stage is derived from the Shahab-3 and uses storable liquid propellant (IFRNA and kerosine). Iran has developed advanced Shahab-3 variants that use smaller and lighter tri-conic re-entry vehicles, smaller stabilising fins and lighter airframes. The Qased shares these small fins. At least two advanced versions of the Shahab-3, with placards denoting them as the Ghadr-F or Ghadr-H, have the same overall length, but different tank lengths. This is clear from a difference in the lengths of cable raceways on the outside of the propellant tanks and seams in the outer skin, where the tank bulkheads are attached. Figure 10 shows a comparison of the Ghadr and the Qased scaled such that the 1st stage diameter matches the 1.25 m diameter of the Ghadr variants. The length of the Qased's cable raceway matches the cable raceway of the Ghadr variant with the longest tanks. The 1st stage parameters for the Qased simulation are derived from this tank size and Shahab-3 engine data from an open source. [18]

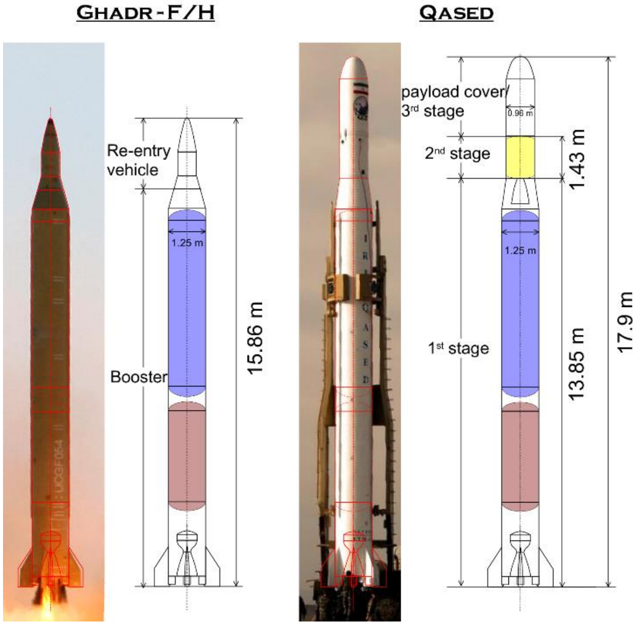

Figure 10: The Qased (right) SLV compared to the Ghadr-F/H (left), with the Qased first-stage diameter scaled to match. The arrangement of the Qased first-stage propellant tanks is notional; it is possible that the oxidizer tank (blue) is mounted below the fuel tank (red). (Original photographs: Reuters)

The estimated tank volume is consistent with the mass flow and the first stage burn time from the screenshot in Figure 9. Unlike the original Shahab-3, at least one of the advanced variants with long tanks has its oxidizer tank mounted in front of the propellant tank, as drawn in Figure 10, but Qased imagery is not clear enough to make sure it shares this arrangement. Visible differences between the Qased 1st stage and the Ghadr are limited to the paint scheme and to the top. The ballistic missile has a conical section that houses guidance equipment and serves as an adaptor for its smaller-diameter re-entry vehicle. The Qased's guidance system is likely placed in its upper stage and its 1st stage conical section is longer and hollow. In the simulation its mass and the mass of the payload fairing are included in the 1st stage deadweight, on the assumption that the fairing is discarded between stage 1 burnout and stage 2 ignition, but the deadweight mass fraction for the stage is still smaller than that of the Ghadr.

Unlike the Safir, the Qased's second-stage engine appears to use solid propellant. With the exception of its burn time, which follows from the graph in Figure 9, performance parameters of this engine are unknown. Video footage from an on-board camera that shows the stage separation shows a fairly large nozzle, which protrudes into the conical section at the top of the first stage. The shape of the second stage and its nozzle seem to match the Salman solid-propellant engine, unveiled in early 2020 and shown in Figure 11 (a). A close-up of the Qased, shown in Figure 11 (b) conforms to this engine's outward appearance.

Figure 11: The Salman solid-propellant engine (a) and the Qased second stage (b). (Video stills from Iribmedia and Iranmedia.org)

With a fairly typical density for solid-propellant, the size suggests a propellant mass of about 1000 kg. It steers through deflecting its nozzle with actuators.

Table 3: Parameters for the Qased

Stage 1	useful propellant mass [kg]	14582
	deadweight factor incl. unused propellant [%]	10.5
	burn time [s]	112
	I_{sp} (sea level) [s]	230
	I_{sp} (vacuum) [s]	255
Stage 2	duration of coast phase	44
	useful propellant mass [kg]	1000
	deadweight factor incl. unused propellant [%]	16.0
	burn time [s]	70
	I_{sp} (vacuum) [s]	270
Stage 3	duration of coast phase	207
	useful propellant mass [kg]	218
	deadweight factor incl. unused propellant [%]	39.8
	burn time [s]	54
	I_{sp} (vacuum) [s]	270
Satellite	mass [kg]	10

There is even less information on the third stage/ satellite kick engine, because it is hidden under a large payload cover. Due to glare on the screen in Figure 9, its burn time is also unclear. The only option for the simulations is to iteratively change the 3rd stage parameters such that the simulated trajectory matches the actual trajectory. The complete parameter set is listed in Table 3.

A specific impulse (I_{sp}) of 270 s chosen for 2nd stage the propellant is a moderate value for a solid propellant with a suitable vacuum expansion nozzle. The deadweight mass fraction (the mass of the stage at burnout as a percentage of the stage at lift-off) for the 2nd stage is fairly typical for a relatively small solid-propellant engine. For the 3rd stage it is significantly higher, because it most likely houses the guidance equipment and thrusters for final course adjustments. The simulations do not allow a distinction between the deadweight mass of the third stage and the payload mass, so the 10 kg satellite mass is an estimate.

In the simulations the computer program iteratively estimated the flight path angle as a function of flight time, such that the resulting satellite orbit matched the reported 444 km apogee and 426 km perigee altitudes (to within less than 0.1 percent). The launch direction was chosen such that the inclination of the orbit matches the reported value of 59.8°. A comparison between parameters on the simulated flight and those in Figure 9 is shown in Table 4.

Table 4: Difference between simulation results and trajectory data shown on the screens in Figure 9

variable	on screen	simulation	difference [%]
h [km]	403.6	400.2	-0.9
V [m/s]	5220.6	5190.6	-0.6
h_{apogee} [km]	447	453	1.3
$h_{perigee}$ [km]	-4121	-4172	1.2

The velocity and altitude are in excellent agreement (less than 1 percent difference). The simulation results and the displayed apogee and perigee of the then-current trajectory differ by only 1.3 percent. These results are quite sensitive to changes in the third-stage parameters. However, given engineering constraints, no other realistic parameter combination gave smaller residual differences with the reported parameters.

With these model parameters, we can now assess how this hardware would perform in a ballistic missile role. The clean modifications remove all mass above stage two, remove coast phases and emplace the warhead. The first-stage deadweight has been reduced slightly, because the payload fairing is removed. The second-stage deadweight has been increased, to account for the addition of guidance equipment.

Figure 12: Maximum range of the Qased, when used as a ballistic missile, against Europe, with two different payloads. (Visualization in Google Earth.)

On simulated maximum-range trajectories, with a payload of 650 kg, the resulting range without Earth rotation is 3337 km, exceeding the IRBM range threshold. This is reduced to 2564 km with a 950 kg payload. The simulated maximum ranges on trajectories towards Europe, with a launch site in Northwest Iran and including Earth rotation, are illustrated in Figure 12.

CONCLUSIONS

The Khorramshahr performance claimed by Iran, and required for the missile to exceed the IRBM range threshold, is only possible with the 4D10 engine if the missile has a significantly smaller deadweight fraction than the original Soviet R-27. However, the different configuration of the missile's airframe, with an inter-tank section and a different front end suggest that the missile deadweight is larger, which makes IRBM performance unlikely. More information, such as a launch video from another flight test, is needed for a better assessment.

The demonstrated flight performance of the Qased as an SLV allows finding well-constrained parameters for a model of the missile. Results show that, if it were modified as a ballistic missile, with a fairly heavy 950 kg payload much of Central and Eastern Europe is in range. With a smaller 650 kg payload the range is extended to include locations further to the west, including much of Germany and Italy, as well as parts of Northern Europe. These values exceed the previously reported 2,200 km range, but it is unclear whether that analysis took into account the effect of omitting the 2nd stage coast phase. While it is by no means certain that the Qased is indeed intended as a step towards a ballistic missile with a longer range than Iran's current arsenal, these results show that it could be.

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[i] This is academic work not reflecting an official position or policy of the Government of the Netherlands.

[ii] The analysis of the Qased is an expanded version of an article published on Breaking Defense [20]