The North Korean Ballistic Missile Program

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For three decades or more, the DPRK has built its capability in liquid propellant ballistic missiles based on Russian liquid propellant rocket motors, guidance and airframe technologies first developed in the 1950s to early 1960s. But the DPRK is now suddenly developing a completely new kind of ballistic missile — the solid propellant KN-11 submarine launched ballistic missile. Although there are many uncertainties about the detailed characteristics and sources of the technologies associated with the KN-11, enough is known to determine that it should at a minimum be able to carry a 1500 kilogram warhead to nearly 450 kilometers or a 1000 kilogram warhead to 600 kilometers or more. This means that when the KN-11 is eventually deployed on diesel-electric submarines, it will almost certainly have the payload and range to carry heavy first-generation nuclear warheads designed for ballistic missile delivery from large areas of ocean. If the DPRK operates its missile carrying submarines in the shallow water of the Yellow Sea, even the most advanced existing US and ROK anti-submarine warfare systems will be ineffective against such a submarine-based threat — making it a highly survivable nuclear weapon delivery system. The largest

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challenge to the success of the KN-11 program will be implementing a sufficiently robust nuclear warhead to survive the extreme vibrations and accelerations that occur during the powered flight of a missile and the roughly equal decelerations from atmospheric reentry. This essay also describes satellite launch vehicles and warhead-carrying ballistic missiles being operated and under development by the DPRK.

Key Words: North Korea, ballistic missiles, KN-11, KN-08, ICBM, SLBM

I. Introduction

Since before the early 1990s North Korea has been steadily building a capability in liquid propellant ballistic missile systems. The bulk of the systems are land-based ballistic missiles that are based on Russian liquid propellant rocket motor and guidance technologies from the 1950s to early 1960s. But North Korea is suddenly in the process of developing a completely new kind of ballistic missile capability — the solid propellant KN-11 submarine launched ballistic missile (SLBM).

The KN-11 uses ballistic missile technologies that are completely different from those associated with liquid propellant ballistic missiles. The sudden appearance of the KN-11 during the last few years has led to a significant mystery about where this new and distinctly different rocket technology came from. There can be absolutely no doubt that these technologies were acquired from outside of North Korea, but the source of these technologies remains unknown in the public record.

The importance of the development of the KN-11 is hard to overstate. One guess is that it is derived from the second stage of the Iranian two stage Sejjil ballistic missile, which appears to have been canceled sometime after 2011. If this speculation about the source of the KN-11 technologies is correct, it is possible to make very rough

estimates of its range and payload characteristics from previous analyses of the Sejjil. These estimates are not necessarily correct, but they almost certainly indicate a lower bound to the range and payload performance of the KN-11.

The extreme significance of the KN-11 is that it is carried in a submarine and should at a minimum have a range of 400 kilometers with a 1500 kilogram warhead to nearly 600 kilometers with a 1000 kilogram warhead. This means that the KN-11 will almost certainly have the capacity and design margins to carry a first-generation nuclear warhead that has been specifically designed for delivery on a ballistic missile.

There is now little doubt that North Korea has finally obtained a laboratory-based capacity to build nuclear weapons of "nominal" yield — about 15 to 20 kilotons.

However, North Korea's two most recent nuclear tests on January 6, 2016 and September 9, 2016 do not mean that North Korea has the ability to deliver such weapons using short range ballistic missiles. Although essentially nothing is known outside of North Korea about the technology used in North Korea's nuclear weapons, it is entirely possible that the most recent tests are of devices that are only workable in a laboratory. It is also possible that these weapons could fly with only minor modifications on a ballistic missile. There is simply so little known about North Korea's nuclear weapons development program that essentially all that can be said with confidence is that they have achieved after 10 years of efforts and five nuclear tests what is called a "nominal" yield.

For a nuclear weapon to be carried by a missile like the KN-11, it will have to survive the extreme acceleration associated with powered flight and the roughly equal deceleration from atmospheric reentry. In addition, it must also survive extreme vibrations generated by the rough combustion of rocket fuel during powered flight. Although these challenges are substantial, the KN-11 will probably provide, along with its submarine launch platform, the least hostile missile environment and the most survivable launch platform needed for successfully deploying a first-generation deliverable nuclear warhead.

One of the big challenges that North Korea will face is operating a force of ballistic missile submarines in the face of US, South Korean, and Japanese antisubmarine warfare systems. These systems are basically the most advanced in the world. However, the fact that these systems are advanced does not necessarily mean they will be effective against this kind of North Korean submarine threat.

The second big area of North Korean ballistic missile development is liquid propellant ballistic missiles based on Russian rocket motor technologies. These liquid propellant ballistic missiles and their components have been used with great ingenuity by North Korean rocket engineers who are unquestionably deeply knowledgeable about Russian rocket motors and related components. These engineers have creatively used these materials to fabricate rockets from components that were intended for different purposes.

In order to understand the character of the North Korean rocket engineering establishment, it is important to appreciate the critical role that culture plays in professional organizations. The genealogy and soul of the North Korean establishment of rocket engineers is almost certainly entirely derived from the Russian expertise that was attracted to North Korea during the catastrophic economic and political collapse of the Soviet Union during the late 1980s and early 1990s.

It is our judgement that the North Korean rocket engineering establishment today was initially established with the indispensable assistance of Russian engineers and scientists. It is equally certain that the many homegrown North Koreans who have been trained by these Russian engineers share this engineering culture. The original spirit of innovation introduced by Russian advisors has been passed onto North Korean junior missile engineers in key roles today. Without this on-going mentoring, it is inconceivable that the DPRK rocket designers and engineers could have succeeded so well and for so long. The most striking example of the creativity of North Korean engineers is the Kwangmyoungseong Satellite launch vehicle. It has a first stage that uses a cluster of four Russian Nodong rocket motors, which are basically closely related to the SCUD-B rocket motor. This rocket motor is roughly twice the size and weight of the SCUD-B

rocket motor and generates roughly twice the thrust.

Another exceptional example of rocket design innovation was the Taepodong-1, which was only flown once in 1998. The Taepodong-1 had a second stage that used a variable thrust rocket motor, probably from the SA-5 strategic long-range surface-to-air missile, housed in a SCUD airframe. Without the substitution of the variable thrust rocket motor for the SCUD-B motor that would normally be used in the SCUD airframe, it would not have been possible for North Korea to control and fly the third stage — most likely adapted from the Russian SS-21 solid propellant tactical ballistic missile — for injection of a satellite payload into orbit.

These innovations in the Taepodong-1 indicate a strikingly creative use of rocket technologies intended for other purposes. Yet in spite of this, essentially every significant innovation in North Korea's liquid propellant rocket systems is derived from Russian rocket technologies.

All of these rocket developments would not pose a serious military or existential threat to South Korea if North Korea could only use these missiles with nonnuclear warheads. In spite of frenetic claims to the contrary, even attacks using many hundreds of these ballistic missiles would not be able to do significant damage to South Korean and US military installations and forces. This is simply due to the very low accuracy of North Korean ballistic missiles and the relatively low counter-military capabilities of low-accuracy conventional munitions. Even a very simple analysis can easily show that if these systems are used to attack hardened and mobile targets, they will be ineffective

There is also no doubt that conventionally armed ballistic missiles would do significant general damage to South Korea's civilian society, but this damage would not be large enough to pose a mortal threat to South Korea's population. In fact, simple passive defense measures of the kind that the Israelis have used with great success could keep casualties from mass ballistic missile attacks quite low — as long as provisions for sheltering and warning have been adequately made and the population can be convinced to follow appropriate procedures.

These conclusions are, of course, entirely reversed with regard to nuclear weapons.

The successful delivery of even a single relatively low-yield nuclear weapon by ballistic missile could cause hundreds of thousands of casualties if it occurred in the downtown area of a large city during the working day. A realistic assessment of the benefits of civil defense against nuclear attack relative to its benefits against conventional attacks quickly leads to the conclusion that civil defense, like missile defense, might at best provide only marginal reductions in the loss of lives against such attacks.

With this background in mind, the discussion in this article will focus almost exclusively on the assumption that North Korea has, or will have, the ability to deliver nuclear weapons on their shorter and possibly longer range ballistic missiles.

This article will first discuss the emergence of the KN-11 solid propellant submarine launched ballistic missile and some of its implications as a newly emerging threat against South Korea. As will be clear from this section, there are many uncertainties in our current knowledge of the KN-11 system, but there is enough known to provide at least a lower bound estimate of its capabilities.

The remainder of the paper will describe liquid propellant rocket motor technologies that have enabled North Korea to build rockets of relatively long range. In particular, in June 2016, North Korea successfully flew a Musudan ballistic missile after a series of failed attempts. The important thing about the Musudan is that it uses a very advanced Russian rocket motor that was originally used, or is closely related to, the motor used in the Russian SS-N-6 submarine launched ballistic missile. This missile is also known as the R-27 in Russia.

The addition of the highly efficient and sophisticated the R-27 rocket motor for use in the Musudan also opens the possibility that it could be adapted for use on the Kwangmyoungseong Satellite launch vehicle. If North Korea decides to substitute the SCUD-B rocket motor currently used in the second stage of the Kwangmyoungseong with the R-27, the new resulting rocket would have the potential to deliver a thousand kilogram payload to the West Coast and Northwest corner

of the continental United States.

Although this theoretical possibility could raise concerns, it is important to understand that such a modification would not simply entail an engine change on the second stage. In reality, it would require the design and construction of a completely new rocket stage. This rocket stage would need to be integrated with the first and third stages of the new rocket. The new design would have to accommodate changes in the vibrations of the rocket during its powered flight, loads, aerodynamics, center of gravity (including the different movement of the center of gravity over powered flight-time), and trajectory shape. This apparently simple modification would therefore be a major undertaking.

The ability to deliver such a payload to this range might well mean that North Korea would have a rocket that could deliver a nuclear warhead to the United States.

However, delivering a nuclear warhead to the United States by ICBM will result in very high deceleration forces during atmospheric reentry — decelerations of about 50 Gs (that is, about fifty times the force of gravity). Designing a nuclear warhead that could survive such a severe deceleration environment would be a major challenge to North Korea. In contrast, the overall acceleration and deceleration environments associated with the flight of shorter range ballistic missiles like the KN-11 makes it much more likely that these missiles will be the first to carry a North Korean nuclear weapon — assuming that North Korea can eventually build a sufficiently rugged, small and lightweight device.

II. The Game Changer: The KN-11 Submarine Launched Ballistic Missile

The technologies needed to build long-range high-payload solid-propellant ballistic missiles are completely different from liquid propellant ballistic missile technologies. The fact that a country like North Korea might have relatively advanced skills with liquid-propellant

ballistic missiles has little meaning with regard to its ability to build solid propellant ballistic missiles. For example, in the case of the Soviet Union, even though it routinely deployed and operated some of the most advanced liquid propellant ballistic missiles in the world it did not develop capable solid propellant intercontinental ballistic missiles (ICBMs) for decades.

There are many types of solid propellants for large ballistic missiles, but the most common is made from particles of aluminum and ammonium perchlorate (NH4ClO4). This powdered material is mixed with materials that act as a binder and with small amounts of special materials to control combustion rates, uniformity and stability during motor operation. Solid propellants are typically mixed and cured inside the motor (which can weigh tons). The process requires extensive experience and considerable industrial capacity to make large amounts of aluminum and ammonium perchlorate particles of highly controlled size and shape. The level of science, artistry, and shop knowledge required to build large rocket motors can hardly be understated.

These facts associated with solid propellant rocket technologies immediately raise questions about how North Korea might have obtained the technology to build the KN-11 solid-propellant submarine launched ballistic missile. There is at this time little known in the public domain about the KN-11, other than it was successfully tested to a range of roughly 500 kilometers on August 24, 2016. Earlier tests over the past several years had indicated the missile was under development, but other than successfully pushing the missile out of the launch tube of a submarine and obtaining an initial ignition of the rocket, the KN-11 had not flown successfully on a full trajectory prior to this test.

Without knowing details of the KN-11 rocket motor technology, it is not possible to predict its potential range and payload.

However, it is entirely appropriate to first ask where the KN-11 technology might have been obtained.

Two countries that have transferred military technologies to North Korea and have demonstrated the ability to produce and operate relatively large solid propellant ballistic missiles are Pakistan and

Iran. In the case of Iran it was in the process of developing the Sejjil ballistic missile when its program came under pressure from countries who were part of the Missile Technology Control Regime (MTCR), which is an informal agreement among countries that have advanced missile technologies to not provide enabling rocket technologies to states that are considered threats to international stability. Iran also had a serious accident that appears to have been either due to sabotage or an accidental explosion of a solid propellant rocket motor that was being manufactured, or both.

In the case of Iran, it appears that its Sejjil solid rocket development program was obtaining significant help from China in the form of solid propellant materials. The Sejjil program came to a relatively sudden end after the accident and once China agreed to stop sending critical propellant materials to Iran. However, there is little doubt that Iran developed significant expertise in the production of solid propellant rocket motors. In particular, Iran was deeply involved in mixing and curing the solid rocket propellants that were used in the Sejjil's rocket motors

In the case of Pakistan, it developed the ability to manufacture the Shaheen I and Shaheen II long-range solid propellant ballistic missiles with substantial technical help from China. It appears that much of the help that was provided by China included the transfer of technologies needed to manufacture the solid propellants needed for the Shaheen I and II. Since both Pakistan and Iran have been involved in transferring various technologies to North Korea, both of these countries must be considered potential sources for some of the solid propellant technologies that are incorporated in the KN-11.

Figure 1 shows a silhouette of the KN-11 from photographs of it in powered flight. Assuming that its diameter is either 1.25 or 1.4 meters, suggests that the KN-11 would have a length of either roughly 7 or 8 meters.

Figure 2 shows silhouettes of the Sejjil and Shaheen II solid propellant ballistic missiles next to silhouettes of the KN-11 with postulated diameters of 1.25 and 1.4 meters. The Seijil rocket motors have a known diameter of 1.25 meters while the Shaheen II's rocket motors

have a known diameter of 1.4 meters. Comparing both of these silhouettes to the second stages of the Sejjil and the Shaheen II strongly suggests that the rocket motor from the second stage of the Sejjil could well be the same motor as that used in the KN-11.

Since there are reasonable estimates of the performance of the Sejjil, it is possible to estimate the potential performance of the KN-11 assuming it is a close derivative of the Sejjil second stage.

Our estimates show that under these assumptions the KN-11 should be able to deliver a 1000 kilogram warhead to a range of about 600 kilometers or a 1500 kilogram warhead to a range of about 450 kilometers. Because our assumptions are based on the very modest

Figure 1.

Figure 2.

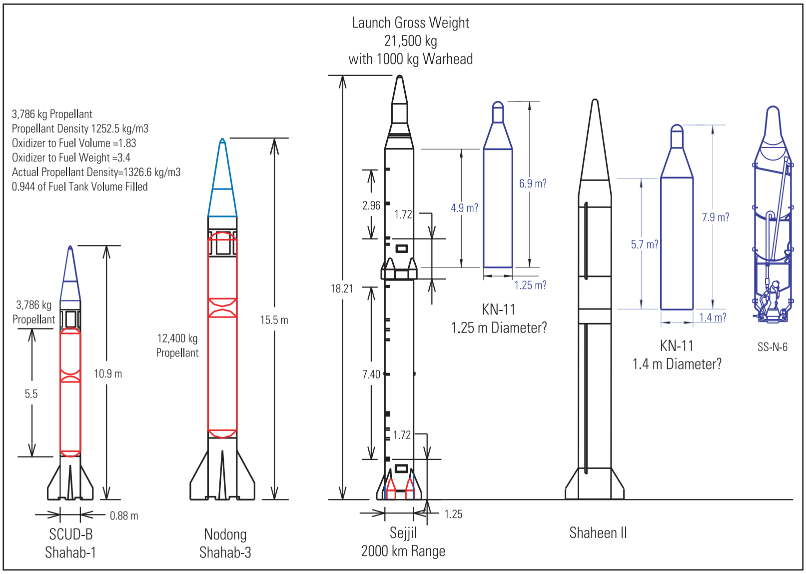


Figure 3.

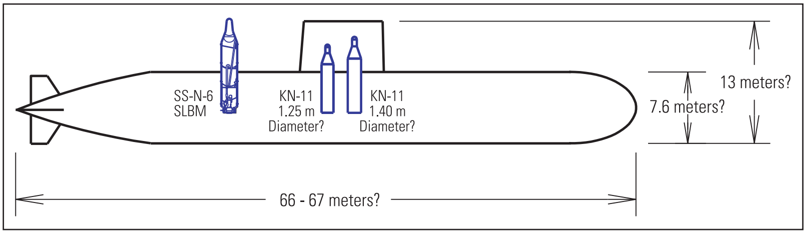


Figure 4.

Figure 5.

performance observed of the Sejjil, longer ranges cannot be ruled out. If our guess that the KN-11 is derived from the Sejjil is wrong, and it instead has a diameter of 1.4 meters, the additional propellant it would carry could give it a range of 800 kilometers with a 1000 kilogram warhead.

It is therefore clear that the KN-11's full range potential will not be known until more specific information is available.

Nonetheless, the general performance of the KN-11 yields important insights about its potential as a nuclear weapons delivery vehicle. The acceleration of the warhead near burnout will result in G forces of about nine or 10 G's, which would be comparable to the G forces associated with the deceleration of a warhead during reentry into the atmosphere. Thus, from the point of view of designing a nuclear warhead that can survive the environment associated with being carried by a ballistic missile, the stresses on the nuclear weapons design will be relatively well-balanced with regard to the missile delivery system.

There are additional quite important insights that are immediately evident.

First, missile defenses like the Terminal High-Altitude Area Defense (THAAD) that are designed to work against attacking missiles that come from a relatively well-defined direction will not be able to readily engage such an all azimuth SLBM. Some might argue that the Navy's Aegis-based SM-3 will be an answer to this threat, but the relatively short flight time of a 400 to 600 kilometer range ballistic missile will result in an Aegis defense that is riddled with gaping holes, even if it were not also susceptible to simple countermeasures like that associated with breaking the rocket casing into many pieces that will look like warheads to the SM-3 interceptors.

A submarine launched ballistic missile with a range of 500 to 600 kilometers will also be extremely difficult to address with modern antisubmarine warfare technologies. The diesel-electric submarine will only be modestly detectable when it is recharging its batteries, which can be as low as five percent of the time when it is on patrol.

Because the submarine need not be near potential targets, it can operate in vast areas of ocean, relatively far from the coasts of North and South Korea and Japan — thereby further increasing the near impossibility of antisubmarine warfare addressing this threat.

Since the mission of a ballistic missile submarine is to remain hidden, this submarine would be operated in ways that make it much less likely to be in environments where it might be detected. Attack submarines, for instance, have missions that require that they move towards potential targets and attack them. Once missiles or torpedoes are launched, the presence of the submarine is known, and adversaries can dispense relatively effective assets like helicopters with active and passive sonar systems. Such scenarios simply don't exist in the case of ballistic missile submarines.

An additional advantage that such submarines have is they are extremely quiet when operating on batteries. In shallow water, the noise background from waves, biological activity, and local shipping creates noise that masks the weak sound signals from a submarine, reducing acoustic detection to extremely short ranges and with high false alarm rates. In addition, the sound-source wave fronts in shallow waters are severely broken up from multiple reflections off the water

surface and bottom. This destruction of the "coherence" of sound in shallow water nearly eliminates the acoustic amplification capabilities of underwater sound arrays used in antisubmarine warfare. Essentially the entire Yellow Sea consists of shallow water of roughly 45 to 50 meters depth. This means the Yellow Sea will be a remarkably viable large area for the deployment of North Korean ballistic missile armed diesel electric submarines.

Other detection methods like magnetic anomaly detection are of extremely short range, of order thousands of feet, and can only be used from aircraft that do not themselves create magnetic signals like those from surface ships. Still other exotic techniques like detecting extremely low frequency radio signals from corrosion and moving propeller blades on the submarine can also be suppressed by proper electrical grounding techniques on the submarine. Both these techniques can be enormously valuable when combined with acoustic detection, but these systems still have very short detection ranges and are totally inadequate for wide-area submarine search

Even the process of trying to acquire and trail submarines as they leave ports can be dealt with by using acoustic mobile submarine simulators, multiple submarines, and delousing tactics during deployment. The North Koreans could be expected to deploy numerous short-range acoustic and other sensors on the ocean floors and surrounding areas that could be utilized by egressing submarines to assure that they have not been acquired by trailers. Once the submarine is at-sea, it would be extraordinarily unlikely that its location would then be found. While there is very little doubt that the US, South Korean, and Japanese navies have been energetically collecting signature data on North Korean submarines while they are involved in tests of the KN-11 and deploying from ports, this data, while very helpful, will not offset the extreme limitations of modern sensors against adequately quiet submarines.

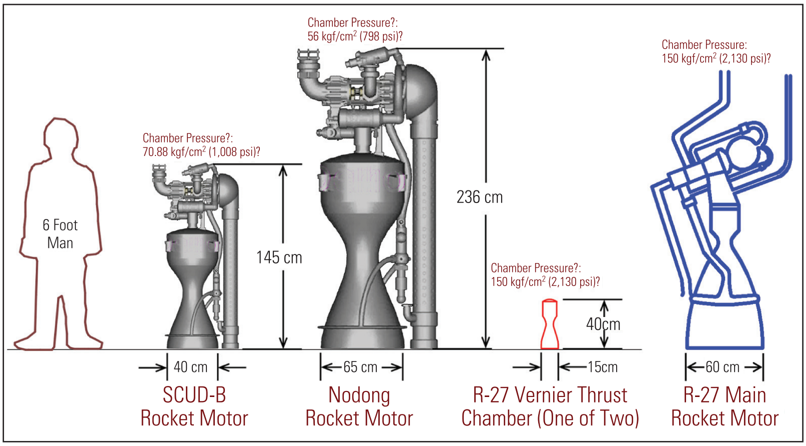
This analysis suggests that when the KN-11 missile becomes sufficiently mature to be considered relatively reliable, it should also be highly survivable, as long as it is able to attack from all azimuths at hundreds of kilometers range.

It is hardly possible to predict when this system might become active. The uncertainties are substantial — it could take decades for North Korea to develop a deliverable nuclear weapon, or it might already be close to having one; new port facilities might be built, for example on the Yellow Sea, to take advantage of the most difficult antisubmarine warfare environments for potential adversaries; refinements in submarine operational practices would also take considerable time. It is possible we could see the beginnings of a functional system within the next five years, but we will not necessarily know that the system is carrying viable nuclear warheads that can be delivered by its missiles.

III. North Korea's Russian Heritage of Liquid Rocket Motors

Figure 6 below shows the four Russian-built liquid propellant rocket engines that are critical components in essentially all of North Korea's liquid propellant ballistic missiles and satellite launch vehicles. The only new rocket system that does not use Russian liquid propellant motors is the newly emerging KN-11 submarine launched ballistic

Figure 6.



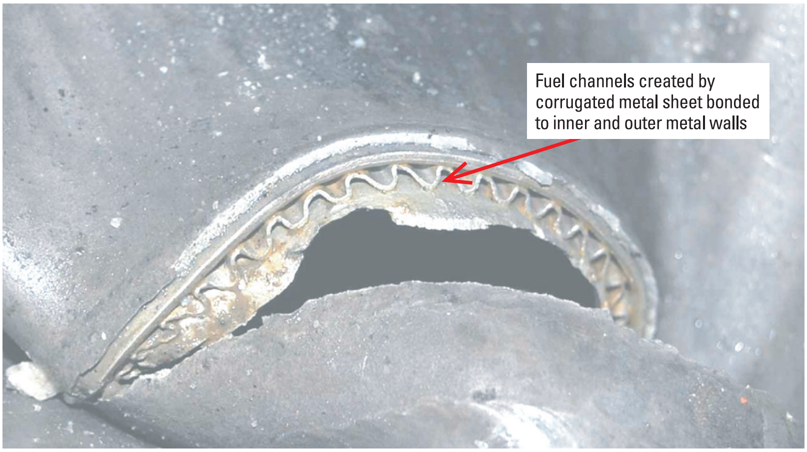
missile (SLBM).

The first two of these liquid propellant engines, the SCUD-B and Nodong motors, are used in the SCUD-B, C, D and Nodong missiles. They are also used in the first and second stages of the Kwangmyoungseong Satellite Launch Vehicle. The R-27 vernier motors (third from the left in figure 1), or a closely related variant, are used as the main propulsion system in the Kwangmyoungseong's third stage. In addition, the R-27 main rocket motor is used in combination with the R-27 vernier motors in the Musudan ballistic missile. The R-27 vernier rocket motors were originally used to generate lateral thrust to control the flight trajectory of the R-27 SLBM during its powered flight and for precise ballistic trajectory injection after main engine cutoff.

All of these motors were originally designed and built in the late 1950s and early 1960s by Russia's Isaev Chemical Engineering Design Bureau and were then handed over to the Makayev Rocket Design Bureau where they were integrated into the Russian SCUD-B land-mobile and SS-N-6 submarine launched ballistic missiles.

Once the engine designs were frozen, the project was transferred

Figure 7.



Fractured Nodong rocket motor casing from the first stage of a Kwangmyoungseong Satellite launch vehicle recovered by South Korea in the Yellow Sea after a North Korean satellite launch on April 13, 2012.

to a "machine plant" for serial production. For the Scuds, this was done in Votkinsk and Zlatoust. The R-27 was manufactured in Krasnoyarsk and in Zlatoust. After that it is not clear how the engines were handled.

These motors have long histories and are well-known in the West to be highly reliable, with design features that are unique to Russian rocket motors.

They are designed to be easily mass-produced with combustion chambers and nozzles that have walls constructed from three layers of metallic sheets. The middle layer of these metallic sheets is corrugated and bonded to the inner and outer metal sheets (see Figure 7) so as to form fuel channels in the nozzle and combustion chamber walls where rocket propellant can flow, both cooling the walls against the high interior temperatures in the motor and heating the fuel for injection into the motor's main combustion chamber. This particular innovation in the construction of rocket motors has made it possible for the Russians to manufacture these motors at high rates and low costs while simultaneously achieving very high levels of performance and reliability in the motors.

The SCUD-B and Nodong rocket motors burn a standard low-energy storable Russian rocket fuel and oxidizer combination called TM-185 and AK-27 respectively. TM-185 fuel is a mixture of 80% kerosene with 20% gasoline and AK-27 oxidizer is a mixture of 73% nitric acid and 27% nitrogen tetroxide. This fuel and oxidizer combination is stable at a wide range of temperatures and is relatively easy to handle in the field, an important requirement for any liquid propellant land-mobile ballistic missile.

The SCUD-B rocket motor generates about 13.3 tons of thrust at sea level and the Nodong generates about twice the thrust of the SCUD-B (28 to 29 tons at sea level). (Note: all tons in this essay are metric tonnes). The R-27 main rocket motor in combination with its verniers also generates about 27 tons of thrust at sea level, but the R-27 is a much more efficient and complex engine that adds very significant new capabilities to the North Korean ballistic missile program. When the R-27 verniers are used without the R-27 main rocket motor, as in the third stage of the Kwangmyoungseong Satellite Launch Vehicle,

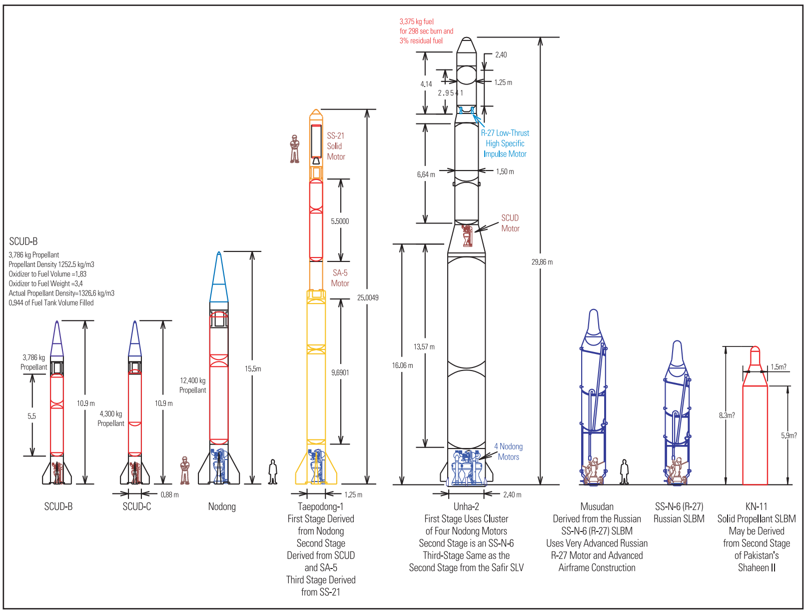
the motor and its two thrust chambers generate about 1.8 tons of thrust at sea level and the same thrust at high altitude when the nozzle has been extended.

IV. The Rocket's Powered by the Engines

Figure 8 shows silhouettes of all the major liquid propellant ballistic missiles that have been demonstrated in tests by North Korea except for the SCUD-ER, which has a one meter diameter and was observed in a North Korean launch in September 2016. It also shows the KN-11, North Korea's new solid propellant submarine launched ballistic missile.

The first two silhouettes starting from the left of figure 8 are the SCUD-B and C. The SCUD-D is almost certainly a close variant of the SCUD-C.

Figure 8.



Both the SCUD-B and C have airframes that appear essentially the same and are powered by the same SCUD-B motor. The major difference between them is that the SCUD-C is able to carry about 20 percent more fuel and oxidizer than the SCUD-B. This is achieved by two design changes. First by increasing the volume of fuel and oxidizer by replacing the two separate propellant and oxidizer tanks with a single large tank that isolates the propellant and oxidizer with a single baffle, and second by increasing the overall length of the new integrated tank.

These modifications may seem simple, but the guidance system also had to be modified to accommodate changes in acceleration and rocket turn rate during the longer powered flight.

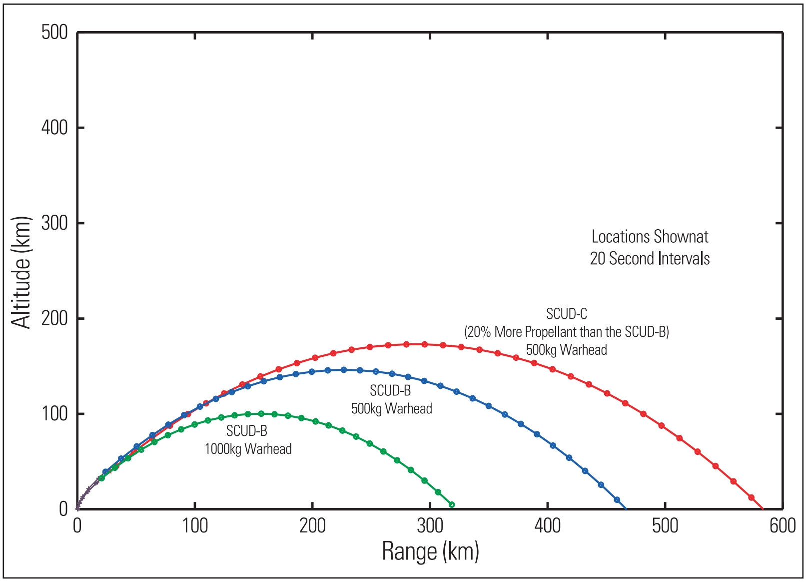
An important factor that makes this modification possible is that the SCUD-B motor is so reliable and well-designed that it can reliably be expected to run for 20 percent longer than its original required 62 seconds in the SCUD-B.

In all likelihood, North Korea's SCUD-B, SCUD-C, SCUD-D, SCUD-ER, and Nodong missiles are purely Russian innovations. However, the ruggedness, reliability, and versatility of Russian rocket motors that were originally designed for other purposes has been a major factor that has allowed North Korea to innovate the Taepodong-1 and Kwangmyoungseong launch vehicles. Essentially all of the innovative liquid propellant rocket designs that have so far been demonstrated by North Korea could only be possible due to the extreme reliability of these Russian rocket motors and their ability to provide power for much longer times relative to what was required by the original Russian rockets that used them.

Figure 9 shows the trajectories and ranges that can be achieved by a SCUD-B with a 1000 kilogram warhead, and by a SCUD-B with a 500 kilograms warhead. As can be seen by inspecting the diagram, the SCUD-B could achieve a range of more than 450 kilometers with a 500 kilograms warhead if it was not aerodynamically unstable during its powered flight and assuming that its guidance and control system is modified appropriately for the change in weight of the warhead.

The third trajectory shown in figure 9, a SCUD-C with a 500 kilo-

Figure 9.



gram warhead, shows that the propellant and oxidizer tank modifications that allows the SCUD-C to carry 20 percent more propellant gives it a range of about 600 kilometers. Thus, the SCUD-C cannot be regarded as a missile that reflects significant gains in rocket technology. It is essentially a slightly stretched SCUD-B that achieves a 600 kilometer range because it carries a lighter warhead and a small amount of additional fuel relative to that carried by the SCUD-B.

The third silhouette from the left in figure 8 shows the Nodong ballistic missile. The dimensions of the Nodong are larger than that of the SCUD-B by the factor 1.414 (square root of two). The Nodong rocket motor is designed using the same basic technology from the SCUD-B rocket motor. It is not an exact scaled up replica of the SCUD-B because simply scaling up the size of fuel injection plates, turbo pumps, and other components would not result in a working rocket motor. Nevertheless, it is very similar to the SCUD-B rocket motor and produces roughly twice the thrust of the SCUD-B.

The Nodong rocket motor, like the SCUD-B rocket motor, has the

ability to function for much longer times relative to those needed in rockets where it was first used. This has made it possible to make relatively minor modifications of the original Nodong rocket similar to those exhibited in the SCUD-C relative to the SCUD-B. The variants of the Nodong that have somewhat longer range relative to the original Nodong rocket are all explainable in simple terms — the steel airframe is replaced with an aluminum alloy airframe, the fuel tanks may be slightly elongated to accommodate more propellant and oxidizer, and the motor provides power at the same rate but for longer times relative to the rocket designs where it was initially used.

The net result is that the Nodong can be best thought of as a single missile design that has several minor modifications, giving it the ability, depending on the design variant, to deliver a 1000 kilogram warhead to a range of between 1000 and 1300 kilometers.

The fourth and fifth silhouettes in figure 8 show the basic features of the Taepodong-1 Satellite Launch Vehicle (SLV) and the Kwangmyoungseong SLV, also known as the Unha-2 or Unha-3. Although their design and implementation is completely dependent on the availability of Russian rocket motors that were intended for other purposes, they demonstrate a very high level of innovation and competence in North Korea's rocket engineering establishment.

The next two silhouettes of rocket systems in figure 8 are of the North Korean Musudan and Russian R-27 SLBM (also known in the West as the SS-N-6).

The Musudan has at this time only flown successfully once. However, the successful launch of the Musudan may indicate the availability of a new rocket motor that might advance the potential capabilities of North Korean rocket systems in the future.

The R-27 rocket motor in the Musudan uses high-energy propellant and when utilized in future rocket systems it will make it possible for North Korea to build rocket systems with considerably longer range and payload than those that utilize SCUD-B and Nodong rocket motors.

The R-27 vernier and main rocket motors burn a completely different Russian fuel and oxidizer combination relative to the propel-

lants used in the SCUD-B and Nodong motors. This different fuel combination is extremely high energy and uses the fuel unsymmetrical dimethyl hydrazine (UDMH) and the oxidizer nitrogen tetroxide (N_2O_4 or NTO). This fuel and oxidizer combination produces very high exhaust velocities in the R-27 motor relative to what is possible in the SCUD-B and Nodong motors and it is used in all of the most advanced Russian liquid propellant ICBMs, SLBMs and launch vehicles that are derived from ICBMs.

However, there is a mitigating factor that could result in much more limited use of the R-27 rocket motor in future North Korean ballistic missiles. This is due to the extreme temperature sensitivity of the oxidizer used in the R-27 motor. The nitrogen tetroxide oxidizer used in the R-27 boils at 21 °C (70 °F) and freezes at -11 °C (12 °F). This extreme sensitivity to temperature variations imposes serious operational limitations on missiles that utilize this propellant — thereby rendering them potentially less attractive for wide application in future systems.

The last silhouette from the left is the KN-11 solid propelled submarine launched ballistic missile.

V. Why Efficient Rocket Motors Are Important

The most important measure of rocket motor "efficiency" is the exhaust velocity of the gases expelled by the motor. As we will now explain, the improved efficiency of the R-27 rocket motor relative to that of the SCUD-B and Nodong has profound implications for the capabilities of new North Korean rocket systems that utilize this more advanced rocket motor.

The efficiency of a rocket motor is captured in an engineering quantity called the "specific impulse." This quantity is used by engineers because it allows for critical performance characteristics of rocket motors to be determined quickly and with minimal arithmetic. For example, the thrust of a rocket motor can be easily determined by multiplying the specific impulse by the weight of fuel consumed per

second.

If a rocket motor has a specific impulse of 230 seconds, and it consumes 60 kilograms per second of propellant, its thrust will be equal to 230×60=13,800 kilograms of force or 13.8 tons of force.

The specific impulse also allows engineers to easily determine a rocket motor's exhaust velocity. The exhaust velocity is simply determined by multiplying the specific impulse by the acceleration of gravity at the earth's surface. Thus, if we assume for purposes of simplicity that the acceleration of gravity at the earth's surface is roughly 10 m/sec^2 (it is actually 9.81 m/sec^2) and the specific impulse is 230 seconds then we can easily determine that the exhaust velocity of the motor is about 2300 meters per second.

The SCUD-B has a specific impulse at sea-level of about 230 seconds and the R-27 has a specific impulse at sea-level of about 262 seconds. In simple terms this means that the exhaust velocity of the SCUD-B and Nodong rocket motors is about 2300 meters per second and the exhaust velocity of the more efficient R-27 is about 2600 meters per second. Although the exhaust speed determines how much force the rocket motor generates per kilogram of fuel consumed, this fact alone does not adequately explain the extent to which an increase in a rocket motor's specific impulse can have on rocket performance.

The first consequence of an increase in rocket motor exhaust velocities for rocket performance can easily be appreciated by imagining an individual sitting on a flatbed railway car that contains a load of uniformly sized rocks.

If the individual throws a rock down the axis of the rails, the car will recoil slightly. Each time a rock is thrown the railway car will recoil at a somewhat larger rate — basically because the weight of the load of rocks on the railway car is decreasing with each throw.

If the individual has the strength to throw rocks at twice the speed relative to earlier throws, they will get twice the recoil with the same rock. This extra recoil is not free, because more energy has to be expended per throw in order to impart twice the speed to the rock. However, when they finish throwing all the available rocks at twice the speed of the earlier throws, the railway car will be going at twice

the speed relative to the earlier case.

If a rocket motor uses "low-energy" fuels, there is not enough energy released in the combustion chamber to accelerate the gases to as high speed as would be the case in a rocket motor where the combustion of fuel in the combustion chamber releases more energy.

So if two engines have the same thrust but one has a higher exhaust velocity, the engine with the higher exhaust velocity will be able to burn proportionately less fuel to obtain the same burnout velocity as the engine with lower exhaust velocities.

In the case of the R-27 versus the SCUD-B or Nodong, the relative exhaust velocities at sea-level are roughly 2600 meters per second for the R-27 and 2300 meters per second for the SCUD-B/Nodong. This means that if all things are equivalent except for the exhaust velocities, the end velocity achieved with the R-27 relative to the SCUD-B class motors would be 2600/2300 =1.13 larger for the R-27.

Since the increased velocity translates into an increase in kinetic energy of the payload of $1.13^2 = 1.28$, this means that the payload with the higher exhaust velocity (the more energetic motor) could accelerate a 28 percent larger mass to the same velocity as the less efficient motor. That is, the more efficient rocket motor could in this example deliver a payload of 28 percent greater mass to the same burnout velocity and thereby the same range as the less efficient motor.

The actual performance increases can be much higher when one considers multistage rockets.

Assuming each stage of a three stage rocket can deliver 13 percent more velocity each, than the three stages in tandem will deliver a payload of fixed weight to a velocity equal to 1.13×1.13×1.13=1.44 times that of the original payload speed. This could be translated into a range increase on a flat earth of two or a payload increase for the same range of two. For trajectories that are already of several thousand kilometers on a spherical earth, the proportional increases in range would be considerably higher.

Thus, the apparently relatively small extra specific impulse in the R-27 motor could have major performance impacts when this motor is incorporated into different rocket systems.

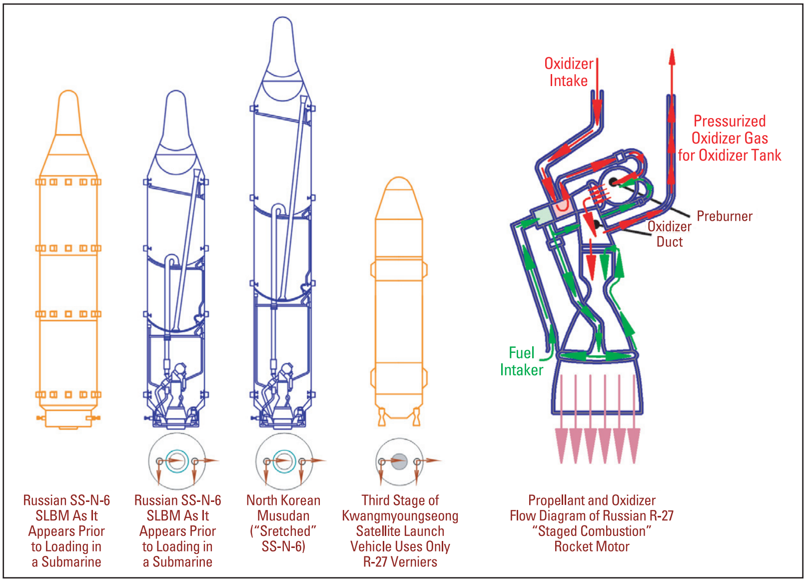
VI. The Musudan Rocket

As already explained, the availability of more efficient rocket motors has benefits that are disproportionately higher than they actually appear by simply looking at the motor efficiencies alone.

The second silhouette from the left in figure 10 shows the interior structure of the Russian SS-N-6 SLBM. The R-27 motor is immersed inside the propellant tank and transmits its thrust to the airframe of the rocket through a funnel shaped baffle. The inner part of the funnel is connected to the bottom of the motor's nozzle and the outer part of the funnel is connected to the airframe. This exotic design makes it possible to shorten the overall length of the rocket so that it can carry relatively large amounts of fuel within the constrained volume of a submarine launch tube.

An important feature of this design is that the funnel-shaped end-baffle not only confines the fuel to the propellant tank, but it also transmits all of the lifting forces from the rocket motor to the rocket's

Figure 10.



airframe. This particular exotic design feature of the R-27 has implications for claims about the use of the R-27 rocket motor in the KN-08, which is a missile that has never been flown and has a configuration of multiple stages that would never be chosen by competent rocket design engineers.

The R-27 motor is an early-generation Russian rocket motor that uses "staged-combustion," a technology that produces higher rocket exhaust velocities than is possible with comparable motors that do not use this unique Russian motor technology.

The right-most silhouette in figure 10 shows how staged combustion is implemented in the R-27 rocket motor.

The use of staged combustion can be understood by first following the path of the fuel and then following the path of the oxidizer.

Focusing first on the flow of fuel into the motor (path shown by green arrows), the fuel turbopump sucks the fuel from the bottom of the fuel tank into the engine. The turbopump delivers the fuel to the bottom of the nozzle where it forces the fuel through channels in the outer walls of the nozzle and combustion chamber. The fuel is heated as it cools the walls of the exit nozzle and combustion chamber and it is then injected into the combustion chamber.

Focusing next on the oxidizer, it is pumped by a turbopump directly into the "preburner" where it is mixed with a small amount of fuel to create a mixture of heated oxidizer and a small amount of combustion products. The heated oxidizer passes through a turbine into an oxidizer duct that delivers the heated oxidizer directly into the combustion chamber where it is mixed with the heated fuel. During the process of injecting the heated oxidizer from the preburner into the oxidizer duct, mechanical energy is imparted to the turbine that drives the propellant and oxidizer turbo pumps.

This type of engine captures large amounts of chemical energy that would otherwise be lost in the form of inefficient combustion and hot gases expelled from turbine outlets. Hence, the R-27 "closed cycle" engine delivers higher propulsive efficiency through higher combustion efficiencies that are subsequently transformed into higher exhaust velocities.

The four silhouettes on the left of figure 10 show how the R-27 and its vernier motors have been used in the Russian R-27 (known in the West as the SS-N-6) SLBM and how North Korea has used these motors for special purposes in two distinctly different applications.

The original SS-N-6 (the second from the left silhouette in figure 10) consisted of a main rocket motor and two verniers that can each swivel along the pitch and yaw axes (see diagram of the back end of the SS-N-6 at the bottom of the SS-N-6 silhouette). This design saves weight relative to a design that would use four verniers that each swivel along a single pitch or yaw axis.

The main rocket motor provides most of the thrust while each of the two verniers provide the lateral thrust needed to control the rocket's flight trajectory during powered flight. The verniers are also used at the end of flight to make refined adjustments to the final velocity and direction of the missile.

As an inspection of the third silhouette from the left in figure 5 shows, the Musudan appears to be simply an SS-N-6 SLBM with slightly elongated propellant and oxidizer tanks, carrying roughly 30 percent more fuel than the original SS-N-6.

North Korea's modifications of the Musudan could show a growing level of sophistication in modifying rockets from their original designs. In order to implement this modification of the SS-N-6, North Korea would need to master the operation of the R-27 rocket motor and the guidance system that controls the vernier motors in the new rocket, which has a different acceleration profile and different rotational inertia. In addition, the SS-N-6 is known to be built from high-strength aluminum alloys. The ability to weld new sections into an existing airframe made from specialized high-strength aluminum alloys could demonstrate yet another advance in North Korean rocket technologies.

However, it is perhaps more likely that the apparent successful flight of the Musudan indicates a much less dramatic increase in the capacity of the North Korean ballistic missile program. The challenges that North Korea would face to actually extend the airframe of an SS-N-6 are quite substantial, and it cannot be assumed that this is how

North Korea actually manufactured a vehicle that has the appearance of an extended SS-N-6.

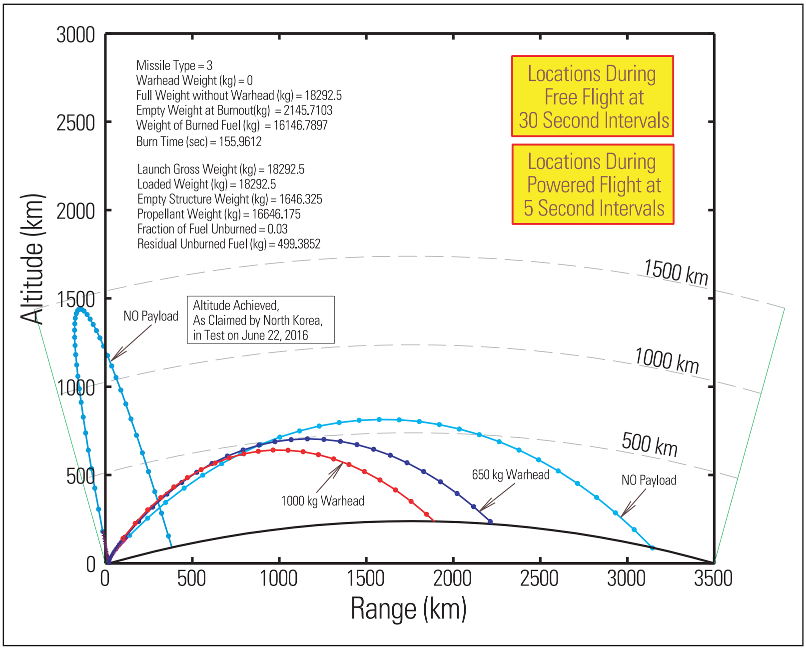
On June 23, 2016, after six flight failures, North Korea finally successfully flew a Musudan missile. The flight trajectory was to an altitude roughly above 1400 kilometers and to a range of about 500 kilometers. This trajectory is plotted in figure 11.

The high apogee and short ground-range for the test flight was almost certainly due to the fact that the Musudan was flown from North Korea's east coast test range and the testers did not want to either overfly Japan or impact too close to ocean areas under Japan's control.

Simulations of the observed June 23 test trajectory can be used to verify a rough model of the Musudan missile.

The model indicates that the Musudan should be able to carry a 1000 kg payload to a range of about 2500 km. This is a significant

Figure 11.



range, but it is much shorter than the 4000 km range that is typically reported for this missile. Analysis based on first principles do not explain why this incorrect 4000 km range continues to be stated and repeated in open literature sources.

With a range of 2500 km, the Musudan could not deliver a 1000 kg payload to Guam. But it can deliver a 1000 kg payload to anywhere in Taiwan and in the northern areas of the Philippine Islands, but hundreds of kilometers short of Manila.

As will be discussed in the section on the Kwangmyoungseong Satellite Launch Vehicle, if the Musudan rocket motor technology is substituted for the SCUD-B rocket motor in the second stage of the Kwangmyoungseong Satellite Launch Vehicle, it could produce a rocket capable of delivering a 1000 kg payload to an approximate range of between 9,500 and 10,000 km.

This possibility might actually be the most important implication of North Korea's mastery of the R-27 rocket motor.

As already noted, the R-27 nitrogen tetroxide oxidizer boils at 21 °C (70 °F) and freezes at -11 °C (12 °F). It also has a low heat capacity — about one third that of water and it strongly dissociates from N_2O_4 to $2NO_2$ as its temperature changes. These properties create significant challenges if this propellant is to be used in land-mobile missiles.

All of the Russian rockets that use this propellant are either in temperature stabilized environments inside submarines or in underground launch silos — even those ICBMs that have been converted into satellite launch vehicles.

In spite of using this highly temperature-sensitive propellant, the Musudan is represented by North Korea as a land-mobile intermediate range ballistic missile.

The high sensitivity of nitrogen tetroxide to temperature changes requires that it be transported separately in temperature-controlled liquid oxidizer containers along with any land-mobile missile (in this case, the Musudan) that uses it as a propellant. However, controlling the temperature of the transported liquid oxidizer before it is loaded into the missile would not be adequate by itself, unless the mobile missile is also temperature controlled.

For example, if the mobile missile is being fueled when it's temperature is very low, not only will the missile airframe and pipes be cold, but so will thermally massive rocket components like the motor and associated turbo pumps — which sits inside the fuel tank and is surrounded by propellant when the Musudan is loaded. Loading nitrogen tetroxide into a very cold, or for that matter a very hot, unfueled mobile missile could have unpredictable results — oxidizer boiling or freezing in fuel lines, at the faces of turbopump inlets, and significant changes in the dissociation constant of the equilibrium, $N_2O_4 \Leftrightarrow 2NO_2$. As a result, a viable mobile missile using this propellant would need to have the temperature of its inner structure controlled as well as the inner structure being designed from the beginning for the physical accelerations associated with moving the missile over uneven ground.

At a minimum, this suggests that the Musudan land mobile missile could be unreliable if it had to be used in either hot or cold weather or moved continuously over rough roads. It may turn out that the Musudan will remain an important psychological accomplishment of the North Korean government, but may ultimately not play a major role in applications that are deemed as militarily essential.

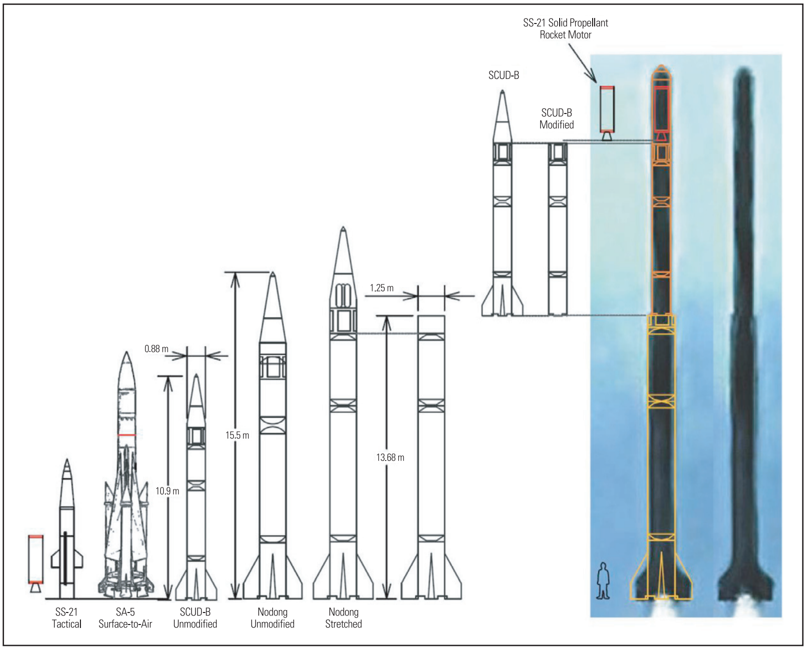
VII. The Taepodong 1 Satellite Launch Vehicle

The Taepodong-1 is an important example of the high level of innovation in North Korea's use of rocket components salvaged from missiles that were originally designed and built for other purposes. The characteristics of the Taepodong-1 can be deduced from photographs and from its known trajectory during North Korea's attempted small satellite launch of 1998.

The characteristics of the Taepodong-1 stages and the rockets from which they were derived are shown in figure 12.

The first stage of the Taepodong 1 is derived from a slightly stretched Nodong, and the second stage airframe appears to be derived from the SCUD-B airframe. However, if a SCUD-B engine

Figure 12.



were used in the second stage, it would not have been possible to orient the third stage for satellite orbital injection. Since the SCUD-B motor can only be operated at full thrust, the SCUD-B would only generate thrust for 65 to 70 seconds before it consumed all the fuel in the second stage airframe and the payload would then have to coast for another 60 to 90 seconds before the solid rocket motor could inject the payload into orbit. This means that the launch would involve coasting without power to an altitude where the small solid-propellant third stage (probably derived from the SS-21 tactical ballistic missile) could correctly orient itself to inject the satellite into a precise orbit. Such a capability, which is common in the West, is simply well

1. 3rd World Missile Development — A New Assessment Based on UNSCOM Field Experience and Data Evaluation, Robert H. Schmucker, 12th Multinational Conference on Theater Missile Defense: Responding to an Escalating Threat, June 1-4, 1999, Edinburgh, Scotland.

beyond the technical reach of the rocket control and guidance systems available to North Korea.

During the time the upper stage was coasting, it would likely have tumbled due to unintended lateral forces imparted to the vehicle during the last seconds of powered flight. The tumbling of the second stage would have serious and catastrophic consequences for the launch attempt as the third stage rocket motor would then not be properly oriented for it to inject itself into orbit.

Robert Schmucker[1] has suggested that the rocket motor used for the Taepodong second stage is not from the SCUD-B, but may instead be from the Soviet SA-5 long-range surface-to-air missile. This speculation is almost certainly correct, as it perfectly fits with essentially all of the publicly available data on the Taepodong 1 launch.

The first stage of the Taepodong-1 was derived from the Nodong ballistic missile. The fuel tanks were stretched to carry roughly about 16,000 to 17,000 kg of propellant. Since the overall weight of the Taepodong 1 is about 22.5 tons and the Nodong rocket motor generates 28 to 29 tons of thrust at sea level, it can lift the total weight of the three stage vehicle.

Based on the known powered flight trajectory to orbital injection the second stage used the liquid rocket motor from the Soviet SA-5 (known in Russia as the S-200) surface-to-air missile. The fuel in the second stage would have to be TG-02, a fuel mixture of 50% xylidine and 50% triethylamine, and the oxidizer AK-27P, which is only very slightly different from that used in the SCUD-B.

The volume ratio of fuel to oxidizer used in the SCUD-B (TG-185 and AK27) is essentially the same as the volume ratio of fuel to oxidizer used by the SA-5 engine (TG-02 and AK27P). The diameter of the exhaust nozzle of the SA-5 motor is also the same as that of the SCUD-B motor and the overall lengths of both motors are nearly the same. An extremely important difference between the SCUD-B and SA-5 motors is that the SCUD-B motor operates at a single thrust of approximately13,800 kg F, while the thrust of the SA-5 engine can be operated at a maximum thrust of 10,000 kg F and a minimum thrust of 3200 kg F. This makes it possible to run the engine at different

thrust levels throughout the powered flight of the second stage so the orientation of the third stage can be controlled until the third stage ignites to inject the satellite into orbit.

Figure 13 shows the calculated launch profile from this model of the Taepodong-1. The calculated launch trajectory is almost perfectly compatible with publicly available information on the Taepodong 1 launch. The calculated trajectory closely predicts the satellite injection altitude, and the ranges of the first and second stages from the launch point.

Figure 14 shows a diagram published by the Japanese Self-Defense Forces that shows where the first and second stages of the Taepodong 1 fell. Referring to figure 13, the first stage propels the vehicle at a high loft angle until it burns out about 95 seconds after launch. The second stage fires at high thrust (10,000 kg F) for about 55 seconds and then fires at low thrust for about 120 seconds until it reaches an

Figure 13. Taepodong 1 Powered and Free Flight Profile

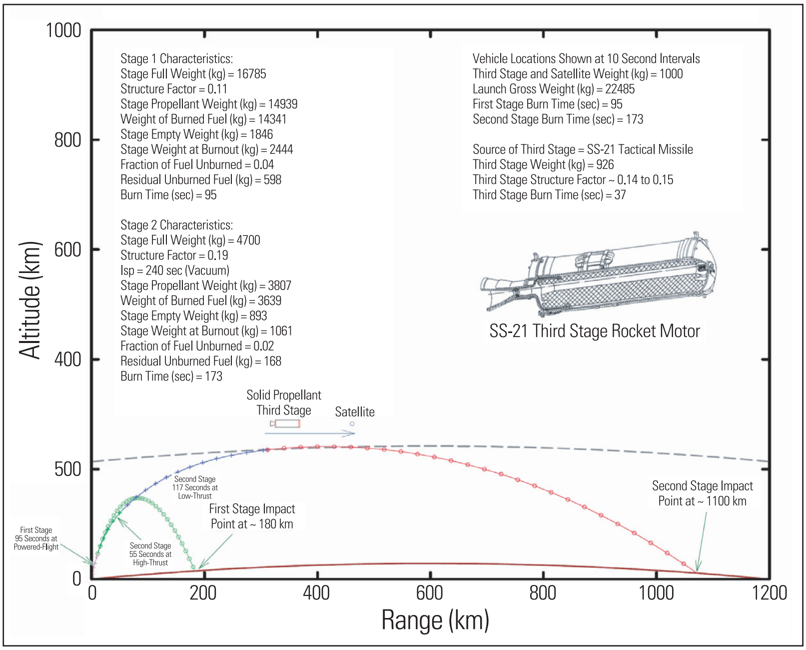


Figure 14. Status of the Flight Trajectory of the North Korean Missile and the Area of Its Descent

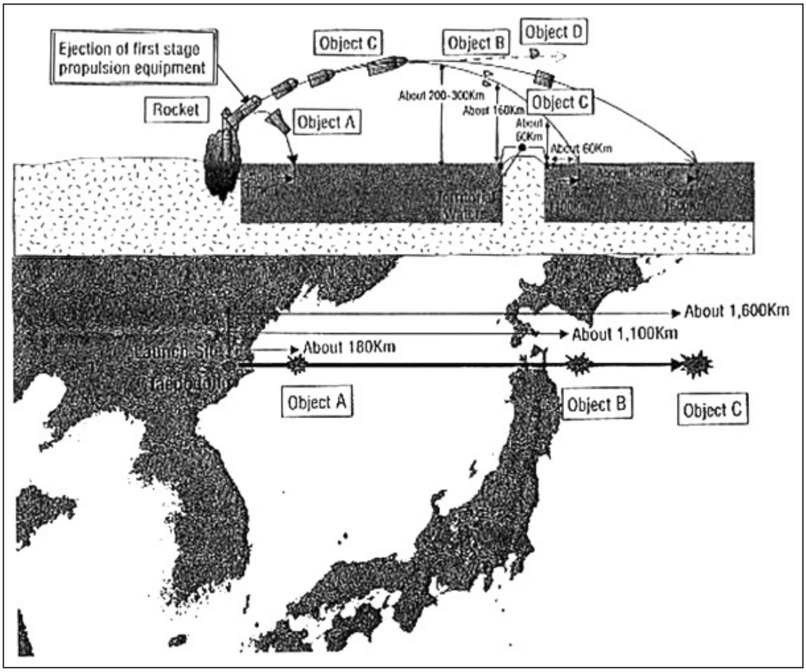


Diagram Released by Japanese Self-Defense Forces

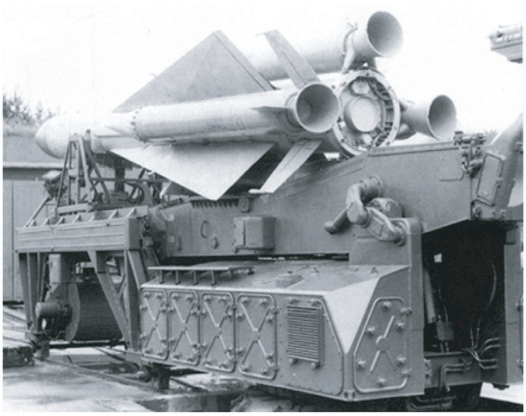
Table 1. Numbers Assumed in and Derived from Calculations

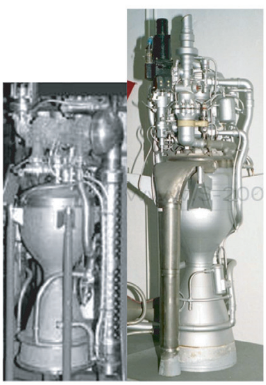
First Stage Burn Time (seconds)	95
Second Stage Burn (seconds)	173.6
Time Second Stage Works at High Thrust (seconds)	55
Time Second Stage Works at Low-Thrust (seconds)	118.6
Total First and Second Stage Powered Flight Time (seconds)	267.6
Injection Altitude (kilometers)	214
Impact Range of First Stage (kilometers)	185
Impact Range of Second Stage (kilometers)	1076

Table 2. Numbers Reported by the North Korean Government

First Stage Burn Time (seconds)	95
Second Stage Burn (seconds)	171
Third Stage Burn (seconds)	27
Total First and Second Stage Powered Flight Time (seconds)	266
Injection Altitude (kilometers)	218

SA-5 Rocket Motor Characteristics



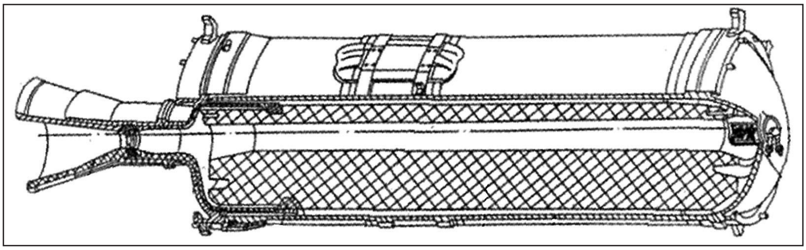


Comparison of
SCUD-B and SA-5 Rocket Motors

SA-5 Variable Thrust Rocket Motor

Fuel : TG-02 and Nitric Acid
TG-02 Samin (50% xylidine and 50% triethylamine)
Volume Ratio of Oxidizer to Propellant: 2:1
(Same as TM-185 and Nitric Acid)
Engine Weight = 119 kg
High-Thrust Mode: 10,000 ± 300 kgf
Low-Thrust Mode: 3200 ± 180 kgf
Time Interval in High Thrust:
Variable Between 0.2 and 50.8 seconds
Probable Vacuum Specific Impulse ~ 240 to 250 sec

SS-21 Rocket Motor Characteristics



Weight of Rocket Motor and Armor Coating (kg)	926
Weight of Armor Coating (kg)	17
Nominal Thrust kgF	9788
Specific Thrust (m/s)	236
Mean Chamber Pressure (kgf/cm^2)	69
Engine Operating Time (s)	18.4-28
Propellant: Ammonium Perchlorate and Aluminum	

apogee of over 200 km, where the third stage motor was to be ignited. For unknown reasons, the third stage failed, but the vehicle appears to have worked properly until this time. At about 40 seconds after the third stage was supposed to ignite (320 seconds after launch), the first stage impacts at about 185 km from the launch site. About 280 to 300 seconds later, the second stage falls at a range of about 1100 km from the launch site, off the east coast of Japan.

Tables 1 and 2 show the extraordinary consistency in all the observed and publicly issued data about the launch. The burn times, injection altitudes, impact distances of the first and second stage, and characteristics of the rocket motors assumed for each of the stages are all perfectly consistent. The sources used for this information include Russian technical discussions of the characteristics of the motors used in all three stages, information from Japan about the impact points of the first and second stage, and information about the injection altitude, and burn times of all three rocket stages. The consistency of all this data almost certainly indicates that the second stage did in fact use the SA-5 rocket motor. The true identity of the third stage rocket motor was not demonstrated in-flight, but its weight, and the 27 second burn time reported by North Korea, very strongly suggest that the third stage is an SS-21 rocket motor.

Shortly after the North Korean Taepodong 1 launch, North Korea claimed that the satellite had been successfully launched into an orbital with a perigee of 218 km and an apogee of 6,978 km. To achieve such an orbit, the satellite would have had to be injected at about 8.9 km/sec. The solid rocket motor would have had a vacuum specific impulse of 265 seconds, and a fuel fraction of 0.85 – 0.90. The satellite would have weighed about 4 to 5 kg. These rocket motor characteristics appear somewhat optimistic relative to those associated with the SS-21 rocket motor.

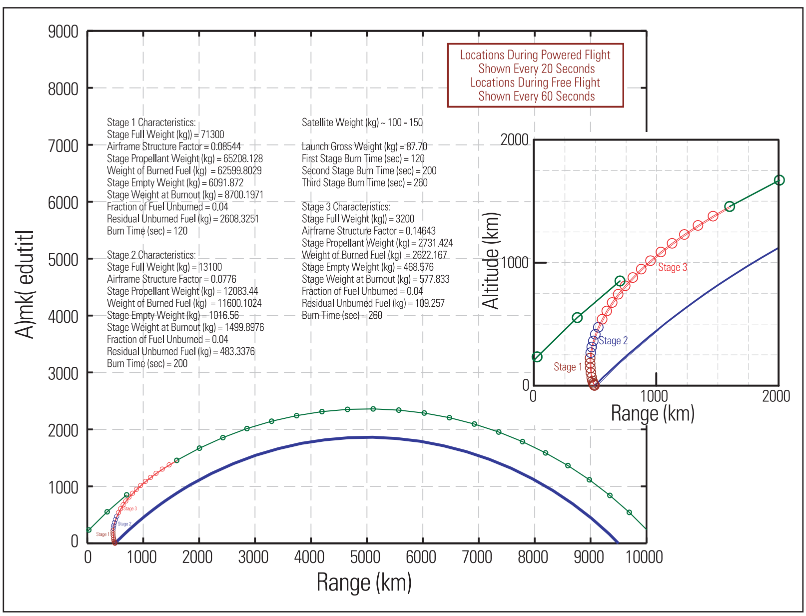
VIII. The Kwangmyoungseong Satellite Launch Vehicle

The Kwangmyoungseong Satellite Launch Vehicle was clearly designed from the beginning for use as a satellite launch vehicle. The design choices that unambiguously lead to this conclusion are the use of a single SCUD-B rocket motor in the second stage rather than a Nodong rocket motor that would have twice the thrust and half the powered flight time. The choice of a small third stage that has a very long powered flight and uses low thrust R-27 vernier rocket motors is yet another clear indication that the Kwangmyoungseong was optimized from the beginning for satellite launches.

Like virtually all of the liquid propellant missiles and launch vehicles built by North Korea, the Kwangmyoungseong only uses Russian liquid propellant rocket motors that were designed in the time period between the 1950s and early 1960s.

The reason for choosing rocket stages and associated rocket

Figure 15.



motors that result in a very long powered flight time is to be able to "fly" a satellite into orbit without having periods of time when upper stages and payloads have to coast under the influence of gravity and momentum (see figure 15). The design choices that make it possible for the Kwangmyoungseong to fly its satellite payload into orbit are exactly the same as the choices made by North Korean designers for the much smaller and much less capable Taepodong-1.

As noted earlier, countries that use small satellite launch vehicles that utilize advanced solid propellant rocket technology motors derived from solid propellant ICBMs like the US Minuteman typically have periods of coasting interspersed with periods of powered flight during the launch of satellites. However, in order to do this the launch vehicles must have rocket motors that can be started or restarted in zero-gravity conditions. In addition, these much more sophisticated launch vehicles have elaborate control systems to maintain the orientation of upper stages and payloads while they are coasting and before main rocket motors are turned on to inject the payload into an orbit.

Since North Korea does not have these rocket technologies their strategy for launching satellites is to simply design at the beginning a rocket that has a very long powered flight time that leaves the payload in its final orbit at the end of powered flight.

The relative sizes of the rocket stages of a long-range ballistic missile or satellite launch vehicle is one of the most fundamental design features that would be established at the very beginning of a rocket's development. Each stage has to lift a different amount of weight and impart an optimum velocity to the higher stages that it is lifting before it runs out of fuel.

The "staging ratios" should be designed so that each stage gives roughly the same increase in velocity to itself and the upper stages and payload that it carries. By matching the stage ratios in this way, a rocket with an initial Launch Gross Weight will be able to place the maximum payload onto a desired trajectory (that is, the payload would be at the desired velocity and direction to achieve its target-orbit).

The factors that determine the staging ratios are not simply the size and weight of each stage. They also include the "efficiency" of each stage's rocket motors and the powered flight times of the rocket stages.

In the Kwangmyoungseong Satellite Launch Vehicle, the second and third stage design choices were made from the beginning to make it possible to have the needed long powered flight time to control and inject a satellite into orbit at the end of powered flight. No rocket designer would choose such long powered flight times unless it was dictated by the inability to control the orientation of upper stages and payloads and the inability to turn main rocket motors on and off during coasting phases where the rocket main motors are not operating.

This is because of the design choice of a long powered flight time results in a high cost in payload weight-to-orbit due to an effect called "gravity losses."

To get a sense of why gravity losses are significant for rockets operating in the gravitational field of the earth, consider a rocket motor acting in the absence of any forces other than its rocket motor. For our example, we assume a rocket stage that accelerates its payload to 2500 meters per second in 100 seconds.

If the same stage is accelerating on a vertical trajectory from the surface of the earth, the combined forces of the earth's gravitational pull and the rocket's motor would only result in the stage achieving a final velocity of 1500 meters per second. Since the acceleration of gravity near the Earth's surface is 10 m/sec^2, the loss in velocity from the force of gravity is, 100 seconds × 10 m/sec^2 = 1000 m/sec. This loss is due to the pull of gravity on the rocket while it's in powered flight and is typically referred to by rocket designers as the "gravity loss."

The loss imposed by the effects of gravity during powered flight in a gravity field depends directly on the time the rocket motor is on. For example if the rocket stage referred to above is instead powered by a motor that is capable of generating twice the thrust for half the time, this means the rocket stage would instead undergo powered

flight for 50 seconds rather than 100 seconds. If the rocket is accelerating when there is no gravitational pull, then it will achieve exactly the same velocity as the rocket that accelerates half as fast for twice the time. However, if the rocket is accelerating in the Earth's gravitational field its final velocity will be $2500 - 50 \times 10 = 2000$ meters per second, resulting in a higher final velocity relative to the more slowly accelerating rocket. This additional velocity can, of course, be traded for the same final velocity but with heavier payload.

The figure below shows the many design choices that could have been used for the Kwangmyoungseong design so that it would be better optimized for a role as a long-range ballistic missile delivery system.

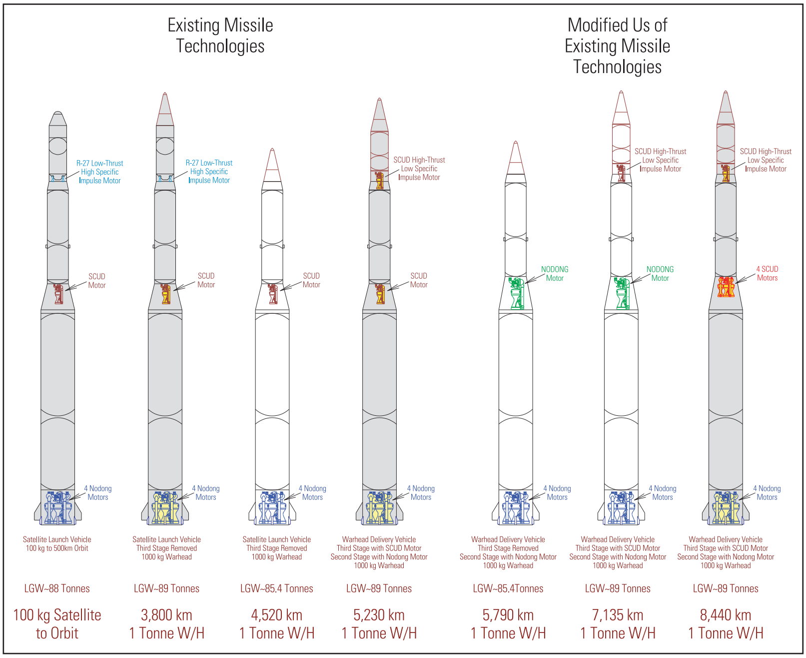
The first of the missile designs on the left side shows the configuration of the Kwangmyoungseong Satellite Launch Vehicle. The first stage contains a cluster of four large Nodong rocket motors, the second stage contains a single SCUD-B rocket motor, and the third stage contains the R-27 vernier rocket motors from the Russian SS-N-6 submarine launched ballistic missile. This vehicle has demonstrated that it can place a satellite of 100 to 150 kilograms into a low-Earth orbit.

The second rocket configuration from the left shows exactly the same satellite launch vehicle except that the satellite and shroud at the top of the third stage has been replaced by a 1000 kilogram warhead. This "reconfigured" satellite launch vehicle can only deliver the 1000 kilogram warhead to a range of only 3800 kilometers.

The third rocket configuration from the left shows a variant of the Kwangmyoungseong vehicle with only its first and second stages. In this case, the two stage configuration has a range 700 kilometers more than that of the three stage version (more than 4500 kilometers). This is because the loss in the velocity at burnout of the second stage from carrying the extra weight of the third stage is not offset by the inefficiency of the third stage when it is carrying a heavy payload.

If the low-thrust long burn-time third stage R-27 vernier motors are replaced with a SCUD-B rocket motor, which has a lower exhaust velocity, but a much higher-thrust and shorter burn-time (in this case about 30 seconds relative to 260 seconds because the fuel load is

Figure 16.



smaller than that carried by a full-length SCUD-B airframe), the gravity losses relative to the long powered flight version of the upper stage are sufficiently reduced to result in an increase in range to more than 5200 kilometers.

The last three configurations, all still using SCUD-B and Nodong rocket motors that have been observed in North Korean ballistic missiles since before 1990, all use shorter burntime stage configurations relative to the Kwangmyoungseong vehicle. The first of these three configurations is simply a two-stage vehicle that has a second stage with a shorter powered flight time because it uses a Nodong rocket motor which generates roughly twice the thrust for half the time relative to the original configuration that uses a SCUD-B rocket motor. The second of the three configurations simply adds a shortened SCUD-B powered third stage, and the last of these three configurations has a second stage that burns twice as fast as the previous postulated

stages with Nodong motors by using a cluster of four SCUD-B rocket motors in the second stage of the Kwangmyoungseong.

Each of these last three configurations can carry a thousand kilogram warhead to greater range — from roughly 5800 kilometers to roughly 7100 kilometers, and finally to more than 8400 kilometers.

All of the propulsion technologies used in these various configurations have been in the possession of North Korea since before 1990. Each of these different analyzed configurations have significantly different engineering design features relative to the others. For example, the airframe of the second stage of the Kwangmyoungseong variant that uses a cluster of four SCUD-B rocket motors would have to be engineered so as to reliably survive accelerations that are four times higher than that of the Kwangmyoungseong second stage that is powered by only a single SCUD-B rocket motor.

North Korea would also have to solve the problem of clustering four SCUD-B motors together, which is not a simple task. Although experience has shown that vibrations from individual motor combustion instabilities are reduced when the motors are clustered, the complexities of clustering separate motors can result in catastrophic motor assembly failures. Such a serious failure was experienced by North Korea during its development of the cluster of four Nodong rocket motors that were ultimately used in the first stage of the Kwangmyoungseong Satellite Launch Vehicle.

Also worthy of note, like the situation with substituting an R-27 rocket motor for the SCUD-B motor in the second stage of the Kwangmyoungseong launch vehicle, very substantial engineering is required to accommodate changes in the structural vibrations, powered flight trajectory modifications, and other critical technical issues that need to be addressed to end up with a truly new missile.

So it would be misleading to consider each of these configurations as readily achievable by simple substitution of rocket components. However, this example serves to illustrate that the designers of the Kwangmyoungseong had many design choices other than what they chose relative to the Kwangmyoungseong Launch Vehicle which has now been used to successfully launch satellites on two occasions.

IX. Could the Successful Flight of the Musudan have Implications for a North Korean ICBM?

Although the Kwangmyoungseong was clearly designed from the beginning as a satellite launch vehicle the question remains whether it could be modified to deliver a 1000 kilogram warhead to intercontinental ranges.

The primary set of technologies that lead to the conclusion that such a modification is possible are the technologies associated with the ability to successfully fabricate the large first stage of the Kwangmyoungseong. This stage consists of a cluster of four Nodong rocket motors along with four vernier motors of uncertain origin that provide the initial heavy lift capability needed to launch a second and third stage onto a ballistic trajectory.

The second stage chosen for the Kwangmyoungseong, when it is

Figure 17.

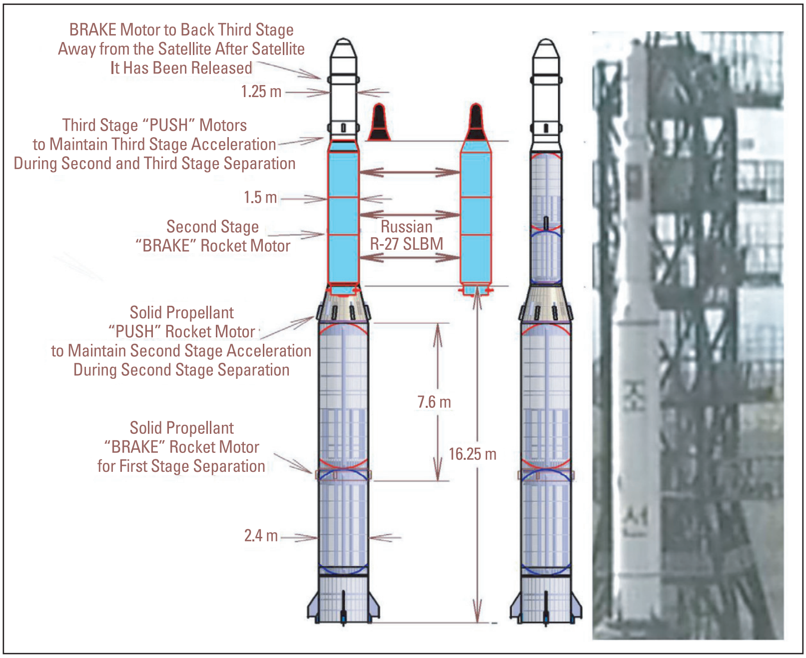
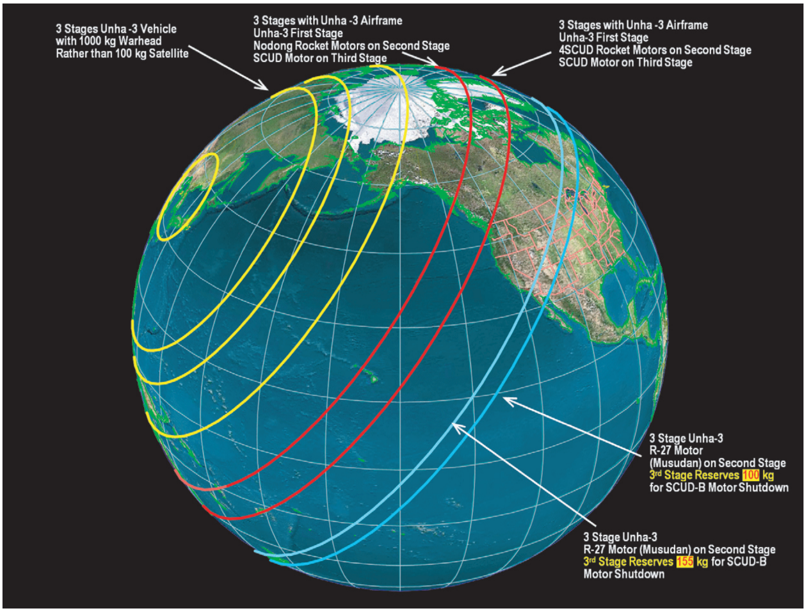


Figure 18.



in the role of a satellite launch vehicle, required that the North Koreans use the SCUD-B rocket motor so as to extend the powered flight time needed to fly the payload into orbit. This choice was followed by a third stage that that was powered for roughly 260 seconds made possible by using the relatively low-thrust and low fuel consuming R-27 vernier motors for its main propulsion. These choices were clearly aimed at producing a satellite launch vehicle, not an ICBM.

However, the question remains about what technologies might be substituted in the second and third stages of the Kwangmyoungseong to convert it to a long-range warhead delivery system.

The first and most striking possibility is to use the Musudan, or better yet, the Russian R-27 for the second stage rather than the current SCUD-B powered second stage. This would reduce the powered flight time of the second stage from about 200 seconds to about 125 seconds. The use of an R-27 airframe would also increase the overall strength of the second stage airframe to accommodate the added

acceleration stresses from the higher thrust R-27 motor.

The third stage would also be modified to carry about the same weight of fuel as the original third stage, but have the stage instead powered by low energy fuel and a SCUD-B rocket motor. The SCUD-B rocket motor would impart about 9G's of acceleration to the 1000 kilogram warhead payload and would shorten the burn time of the third stage from 260 to 50 seconds.

The combined effects of the shorter burn times of the second and third stages, and the more efficient rocket motor in the second stage would result in a rocket that could deliver a 1000 kilogram payload to a range of approximately 9500 to 10,000 kilometers.

The large uncertainties in the actual range of such a missile are due to the extreme sensitivity of the achievable performance in the SCUD B powered third stage of the postulated rocket. We believe these estimates are sound, but we do not know if North Korea could ultimately produce such a third stage.

However, there are no technical barriers that we can find that would limit North Korea from achieving such performance capabilities.

X. Implications of an ICBM Derived from the Kwangmyoungseong SLV

The possibility that North Korea could modify the Kwangmyoung seong Satellite Launch Vehicle to a rocket system capable of delivering a 1000 kg payload to the West Coast and Northwest corner of the continental United States does not mean that North Korea has the ability, or is likely to have the ability, to use this postulated ICBM to materially threaten the United States with a nuclear attack.

It is unlikely that North Korea now has a nuclear weapon that weighs as little as 1000 kg. It is also unlikely that such a first-generation nuclear weapon would be capable of surviving the unavoidable 50 G deceleration during warhead reentry from a range of nearly 10,000 kilometers

As such, the possible future existence of such a modified North

Korean Satellite Launch Vehicle will materially pose little or no immediate threat to the United States.

It is also unlikely that there will be any surprise introduction of this technology into the Kwangmyoungseong SLV. National Technical Means (satellite imagery and high-altitude aircraft reconnaissance) would provide essentially near real-time information about any effort by North Korea to assemble such a missile.

The characteristics of the second and third stage would likely be readily identified as long as North Korea made no special attempts to shroud critical parts of the different stages as they are assembled.

The current third stage of the Unha-3 Satellite Launch Vehicle has a distinct appearance relative to that of a third stage that would be modified as part of the conversion. However, North Korea could make special efforts to interfere with US and other National Technical Means by shrouding critical sections of the rocket stage during assembly of the full vehicle.

If the rocket motor assembly in the second stage is not intentionally concealed during assembly, the second stage should also be readily identified as either that for a Satellite Launch Vehicle, or an alternative long-range delivery vehicle.

The long assembly process would present a technically easy opportunity to destroy the rocket well before it is ready for launch.

Although the destruction of this vehicle would be technically easy to execute, a decision to act would present serious political dilemmas for decision-makers.

The current US Ground-Based Missile Defense system is, and will remain, totally unreliable — and will therefore not provide a US president with a "wait and see" option.

The North Koreans have already demonstrated in the most recent launch of the Kwangmyoungseong (February 9, 2016) the ability to create numerous simple decoys that would defeat the infrared homing Ground-Based Missile defense interceptors. This outcome would be achieved by cutting the third stage of the delivery rocket into numerous pieces that would be indistinguishable from warheads to infrared homing interceptors.

An alternative policy option for dealing with the perceived threat from such a long-range rocket would be to declare that any indication that such a rocket is being assembled will result in an attack on the rocket before it is ready for launch. This policy could be quite problematic as it would establish a "red line" that would trap decision-makers into taking actions in situations that might be ambiguous. On the other hand, such a policy could set a clear and unambiguous warning to North Korea about rocket activities that will not be tolerated.

XI. The KN-08 and Other Long-Range Land-Mobile Liquid Propellant ICBM Variants

The paradox associated with the KN-08 is simple; why would a country like North Korea with modest industrial capabilities choose a missile design that would be tremendously challenging to implement? This question might be restated in yet other terms: why would a country with much more advanced rocket technology like that in Russia or the United States choose such a sub-optimal design that could instead be implemented in a much more sensible configuration that would give higher performance and also be easier to implement?

The significance of these questions is further amplified when it is asked against the backdrop of the technical history of North Korea's tremendous design innovations — which has demonstrated a series of dramatic successes in rocketry that have circumvented its severe industrial and technical limitations.

The source of the claims that the KN-08 mobile land-based liquid propellant ICBM as a real system that is currently under development by North Korea can be traced to implicit assumptions that mockups of rockets and missiles shown in North Korean parades must be real systems. Yet even a careful review of the literature on the KN-08 indicates that nobody has any idea what motors would be used by this system, nor how such a liquid-propellant rocket that has never been tested in any form could be seriously considered as an early indication

of a North Korean land-mobile ICBM.

The two photographs below show on the left one of six KN-08 mockups that were observed in an April 15, 2012 military parade in Pyongyang. The photo on the right shows a mockup that appeared on October 10, 2015. Since there is no technical reason to choose one implausible design relative to another, the new mockup can either be identified as a new version of the KN-08 or yet another new and totally untested land-mobile liquid propellant ICBM that is under develop-

Figure 19.

KN-08 Mockup Observed on April 15, 2012

KN-08 Mockup Observed on October 10, 2015

ment by North Korea.

If the new mockup is in fact a redesign of the KN-08, it shows a fundamentally different upper stage configuration of the missile. The parts of the missile that were initially identified as the second and third stages of an ICBM have now been given expanded diameters to match that of the first stage in the earlier mockups.

As already discussed extensively in the earlier part of this paper, the relative sizes of the rocket stages is one of the most fundamental design features that would be established at the very beginning of a rocket's development. Each stage has to lift a different amount of weight and impart an optimum velocity to the higher stages that it is lifting. This observation immediately raises the question of why two such different but similar missiles would appear over such a short period of time?

Figure 20.

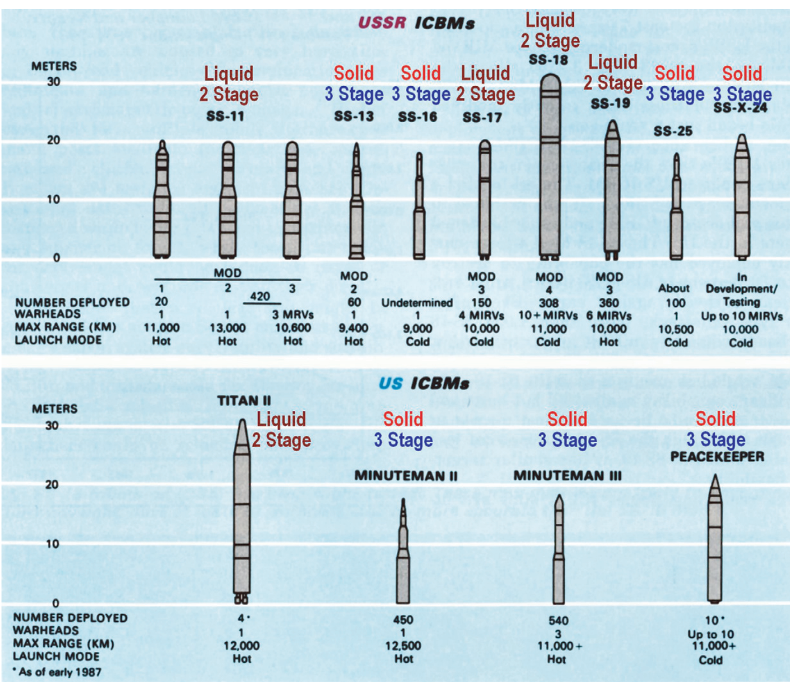


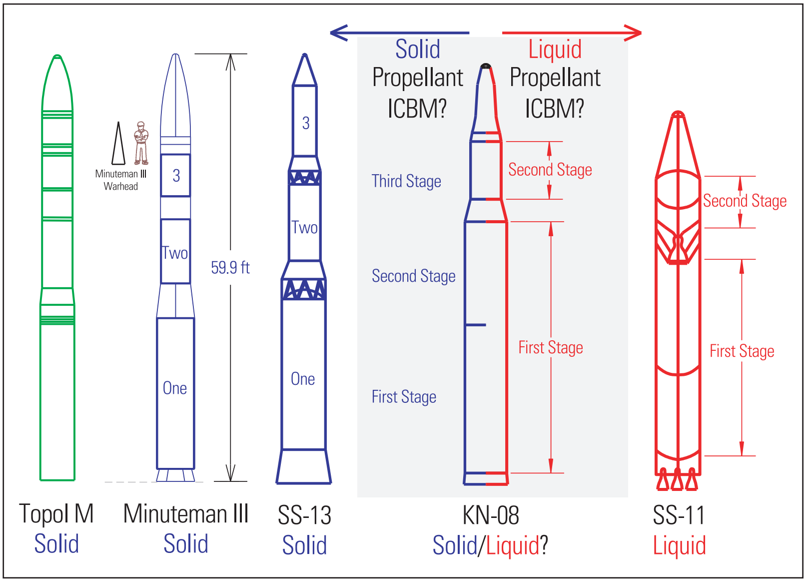
Figure 20 shows a roughly historical summary of the multistage ICBMs built by the United States and Russia over the many decades of the Cold War.

In all cases, the liquid propellant ICBMs have two stage designs and the solid-propellant ICBMs have three stage designs.

Figure 21 shows details of Russian and US solid propellant ICBMs and the simplest Russian liquid propellant ICBM — the SS-11, which is implemented as a two-stage vehicle.

The differences in the staging configurations of solid propellant and liquid propellant ICBMs is a consequence of the different propulsive characteristics of solid and liquid rocket motors and their related technologies. Solid rocket technology leads to a very rugged airframe structure and lower specific impulse rocket motors relative to liquid propellant systems. The important offsetting factor that makes the lifting capacity of solid propellant ICBM rocket systems competitive with liquid propellant ICBM systems is that solid propellant motors typically burn about twice as fast as their liquid propellant counterparts.

Figure 21.



This means that the gravity losses associated with solid propellant systems are significantly lower than those of comparable liquid propellant systems. When the full arithmetic and technology constraints of each of these different types of rockets are properly considered, optimally designed liquid propellant ICBMs turn out to be most efficient if they have two stages and optimally designed solid propellant ICBMs are most efficient with three stages.

In the case of liquid propellant ICBMs that have been converted to satellite launch vehicles, an upper stage is added along with the satellite to position the satellite for orbital insertion and to add some velocity to the satellite payload. Such satellite launch systems are in fact optimal with three stages, but their ICBM antecedents are optimized only when they have two stages.

Given all these considerations, the unexplained issue remains — why would a country that had such a fantastic and sophisticated engineering infrastructure choose to commit precious national resources to building such a sub optimal, complex, and difficult to implement three stage liquid propellant ICBM when the natural choice would be to design a much easier to implement two-stage design?

Adding to these and other technical considerations is the fact that no country has been able to, or has sought to deploy, a liquid propellant mobile ICBM. This again, is not a fact of science but is instead a fact of military technology. The complexities of operating liquid propellant mobile missiles that use sufficiently energetic propellants so that their size and weight is viable in a mobile role are so great that essentially all countries that have considered mobile long-range missiles have ultimately settled upon using advanced solid propellant rocket technologies.

Until there is very clear evidence that North Korea is breaking from its tradition of cleverly designing rocket systems that are well within reach of its limited industrial capacity, the KN-08 and other such variants must be considered as simply systems paraded for purposes of political perception.

XII. Concluding Remarks

North Korea is a dangerous and potentially unstable state that has been developing ballistic missiles based on Russian liquid propellant rocket motor technologies since before the early 1990s. It has a long history of extremely innovative and competent uses of these rocket motors and related technologies for purposes that are quite different from the rocket systems where these motors and technologies were originally used.

More recently, seemingly out of nowhere, North Korea has suddenly developed the capacity to build large solid rocket submarine launched ballistic missiles like the KN-11. Just as in the case of its liquid propellant missile programs, it is overwhelmingly clear that the technologies for producing this missile came from sources outside of North Korea. This development, which has emerged over a very short time — in the last several years — indicates that attempts to block North Korea from obtaining highly sensitive military technologies have seriously failed.

However, it is a grave mistake to assume that the threat from North Korea is basically derived from these ballistic missile capabilities. As almost any modestly competent analysis will show, if these ballistic missiles are armed with conventional warheads and have accuracies of many hundreds of meters, they will pose little or no real military threat to South Korea. Of course, in large numbers (hundreds of missiles that can deliver 500 kilogram to 1000 kilogram conventional explosive warheads), they could do significant general damage to urban areas. However, in spite of such damage, a well-implemented civil defense program aimed at providing expedient shelter to populations under attack could guarantee that innocent civilian casualties could be kept quite minimal.

The real threat to South Korea, Japan, and China from North Korea is that it has now developed nuclear weapons. Even this threat is still ambiguous at this time.

It is clear that North Korea is now able to produce a "nominal" yield nuclear device that is probably confined to laboratory settings.

However, so little is known about the North Korean nuclear weapons development program that it cannot be ruled out that the devices that have been tested in laboratories have not been designed from the beginning to make it possible to readily modify them for carriage on a ballistic missile. A best guess is that this is not the case, and North Korea is probably many years away from being able to deploy a nuclear weapon that can be carried on a ballistic missile. But "best guesses" can hardly be a comfort for those who could be the targets of such an attack.

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