Vol. 47, No. 2 April 2018

PHYSICS & SOCIETY

A Publication of The Forum on Physics and Society A Forum of The American Physical Society

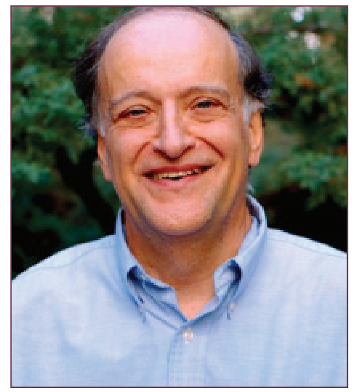
From the Editor

Good news: we are getting some controversy stirred up. The article by Lieber and Press in the last issue has generated one reply article, by Frank von Hippel plus two letters to the Editor, one of which is by Alvin Saperstein, who also wrote an article on that issue. I hope our good luck continues.

For several reasons, most of them troubling, the issues of nuclear proliferation and disarmament are becoming of great current interest again. We have in this issue two articles on the topic: one is by Ted Postol, a well-known arms control expert from MIT. Because of the importance of this article I have given it a very major exemption of the length limit rules. My acquaintance with Ted goes very far back to the time when he was doing academic Physics, trying to figure out how to obtain neutron scattering results from ^{3}He without turning the sample into ^{4}He too fast. The second article on North Korea is by Prof. Bell, a political scientist who knows how to talk to Physics audiences: I met him when he gave a Physics Colloquium in my Department. We also have articles on the Mather congressional Fellowship program for undergraduates (I owe this one to Tabitha Colter, our Media editor) and on innovations in Physics teaching, which comes via Laura Berzak Hopkins.

We also have some news for you: the Forum is organizing a session on arms control at the APS April meeting. One of the speakers is Ted Postol and the other two will have articles in the July issue.

Remember again that this newsletter is dependent on contributions obtained largely by the readers and members of the Forum and their friends. My definition of what is an appropriate topic is very broad: we past issues, particularly October 2017, for some specifics.



Oriol T. Valls, the current P&S newsletter editor, is a Condensed Matter theorist.

Oriol

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IN THIS ISSUE

FORUM NEWS

2018 April Meeting Forum

At the 2018 APS April meeting the forum is sponsoring Session C06 "Nuclear Weapons and Ballistic Missile Defense." Joel Primack will be the chair. The venue is room B130 and the session goes from 1:30 to 3:18, on Saturday April 14. The titles and speakers are

"North Korean Long-Range Ballistic Missiles and US Missile Defenses" by Ted Postol

"Missile Defense and Space Weapons" by Laura Grego

"US Nuclear Weapons Modernization" by Roy Schwitters

LETTERS

Dear Editor:

Since the beginning of the nuclear weapons age, there has been a continuous "intellectual;" dispute between advocates of "nuclear war" and of "nuclear deterrence". Equivalently, the dispute is between the reliance upon "counter force" technology – relying upon increasing missile accuracy, knowledge of target locations, and C3I – and "counter value technology – relying upon survivability of the retaliatory forces. Over the years the U.S. has developed both capabilities, though its publically issued governmental policies have more frequently emphasized "MAD" – mutually assured deterrence". Lieber and Press cite increasing capabilities of required counterforce technology to seemingly press for a decreasing emphasis on nuclear weapon limitation and an increase of reliance on counter force security policies because of their seemingly increased ability to wipe out the retaliatory weapons required for effective deterrence. (They do admit that such a re-emphasis on counter force can be a significant threat to global security.) However, it should be noted that nowhere in their article do they establish significant threats to the SLBM force – the retaliatory missiles constantly prowling deep underwater in the Earth's vast oceans. Nothing in their vaunted C3I improvements, given the known laws of physics, will be able to hinder a devastating retaliatory blow following any possible counter force attack on the existing SLBM forces which will survive. Thus their apparent call for a re-emphasis on counter force strategies, with consequent de-emphasis on nuclear arms limitation efforts, is not only dangerous to world stability but unnecessary for our national security - which should continue to depend upon MAD (Mutually Assured Destruction).

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Dear Editor,

In the January issue, Keir A. Lieber and Daryl G. Press argue that emerging technologies are creating a "New Era of Nuclear Arsenal Vulnerability." We share the authors' interest in how new technologies can influence nuclear security, but we are not convinced that critical shifts have occurred or are inexorably on their way.

The longest section of Lieber and Press's article recounts how missile accuracy has improved since the 1980s, making hardened missile silos more vulnerable to attack. Here the technical point is credible, but the strategic importance is limited. Only the US and Russia keep a significant fraction of their nuclear weapons in silos, and their vulnerability has been recognized for decades. This is one reason why nuclear weapons are deployed on submarines, land-based mobile launchers, and bombers, which maintain a retaliatory capability largely immune to the "accuracy revolution."

The burden of the authors' argument thus falls to the "sensor revolution," where the technical discussion is much weaker. This section amounts to a catalog of broad "technological trends," all on the side of "seekers." While it is reasonable to predict that sensors and their platforms will improve, so will the tactics and technologies that counter them. Weapons platforms will diversify, potentially to autonomous systems, networked sensors may grow more vulnerable to electronic warfare, and anti-satellite capabilities will advance. Without a comparative analysis between hiders and seekers, we are not persuaded by the authors' suggestion that seekers will gain the edge.

Statements about the growing effectiveness of conventional weapons against nuclear forces (e.g., "conventional weapons can destroy most types of counterforce targets") are also too broad and unsupported to take at face value.

Certainly many types of technology are improving, but it does not follow that a dramatically new era is dawning. Demonstrating that new technologies will "undercut the logic of future nuclear arms reductions" and make arms racing "nearly inevitable" would, in our view, require much stronger evidence than Lieber and Press provide.

Sincerely,

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The computer revolution has transformed nearly every aspect of our world. In "The New Era of Nuclear Arsenal Vulnerability" we describe how the dramatic improvements in guidance systems and remote sensing are making nuclear forces more vulnerable to disarming strikes, and hence complicating the mission of deterrence.[1]

Alvin Saperstein shares our concern that efforts to exploit these new "counterforce" improving technologies may trigger dangerous arms races, but his call to deemphasize such capabilities overlooks two factors: First, effective counterforce capabilities could be extraordinarily valuable if an adversary (such as North Korea) began to threaten or employ nuclear weapons during a war. Second, counterforce capabilities – including improved sensors, better command and control systems, and pinpoint-strike weapons – will be developed by the United States to enhance U.S. conventional forces. As long as the United States is committed to fielding the most powerful conventional forces in the world, it will deploy capabilities that also render adversary nuclear arsenals vulnerable.

Saperstein also believes that concerns over arsenal vulnerability are overblown because submarines are inherently secure. This was not true in the past, however, and we doubt it will be true in the future. There were periods of the Cold War in which the United States trailed every deployed Soviet ballistic missile submarine.[2] Today the United States is building a new generation of submarines that must not merely evade the sensors that Russia and China deploy today, but also those that will be developed over the next 30-40 years, a daunting challenge given the rapid pace of technological change. The problem for Russian and Chinese submarines is even greater, given the United States' technological lead in undersea warfare and ongoing investments in those areas.

Rachel Carr and Thomas MacDonald note that although hardened sites are growing more vulnerable, few countries rely on missile silos to protect their nuclear forces. However, many nuclear-armed states store their aircraft and mobile missiles in hardened shelters, protect their weapons in reinforced bunkers, and control their arsenals from hardened command sites. Those facilities would be prime targets in any disarming strike. Moreover, as accuracy continues to improve, hardened sites are becoming more vulnerable to the lower-yield nuclear weapons that the United States and other countries are developing, as well as to conventional strikes.

Carr and MacDonald also note that countermeasures can foil efforts to locate or strike nuclear targets. We agree, and for this reason we believe that countries with considerable resources, such as the United States, will have an easier time keeping nuclear forces secure than poorer and technologically limited countries. Our point is that the computer revolution has transformed the competition between "hiders" and "seekers." A few decades ago, the job of mobile missile operators was simpler, because there were few feasible means for adversaries to monitor large deployment areas, especially those deep in one's own territory. Today, mobile missile operators have a much tougher job: for example, with timing their moves to avoid expanding constellations of radar satellites, countering unattended ground sensors, and anticipating and blocking all the other means of locating mobile forces.

In 1980, John Steinbruner and Thomas Garwin punctured the fears, popular in that era, about the vulnerability of strategic nuclear arsenals.[3] Their analysis identified a set of technological breakthroughs that would have to occur for nuclear forces to become susceptible to disarming strikes. That seminal article is worth rereading today, because each of those technological breakthroughs – and many more – have become reality.

The strategic deterrence community has grown complacent. Almost every aspect of the nuclear deterrence equation

1 Keir A. Lieber and Daryl G. Press, "The New Era of Nuclear Arsenal Vulnerability," *Physics and Society*, Vol. 47, No. 1 (January 2018), pp. 2-5. The longer, more technical version of the argument appears in Keir A. Lieber and Daryl G. Press, "The New Era of Counterforce: Technological Change and the Future of Nuclear Deterrence," *International Security*, Vol. 41, No. 4 (Spring 2017), pp. 9-49, (https://www.mitpressjournals.org/doi/abs/10.1162/ISEC_a_00273).

2 See See Austin Long and Brendan Rittenhouse Green, "Stalking the Secure Second Strike: Intelligence, Counterforce, and Nuclear Strategy," *Journal of Strategic Studies*, Vol. 38, Nos. 1–2 (2015), pp. 38–73; Owen R. Coté Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, R.I.: Naval War College, 2003); and Peter Sasgen, *Stalking the Red Bear: The True Story of a U.S. Cold War Submarine's Covert Operations against the Soviet Union* (New York: St. Martin's, 2009). See also our discussion in Lieber and Press, "The New Era of Counterforce," pp. 35-37.

3 John D. Steinbruner and Thomas M. Garwin, "Strategic Vulnerability: The Balance between Prudence and Paranoia," *International Security*, Vol. 1, No. 1 (Summer 1976), pp. 138–181.

has changed since the Cold War: weapons are more accurate, sensors are more effective, and now target sets are far smaller. It would be strange if all the old "truths" about nuclear deterrence remained valid despite these revolutionary changes. Coming to terms with the reality of a new era of nuclear arsenal vulnerability is the first step toward a better understanding of the global political and strategic implications.

Keir A. Lieber, Georgetown University
Daryl G. Press, Dartmouth College
March 1, 2018

ARTICLES

North Korean Ballistic Missiles and US Missile Defense

By Theodore A. Postol[1], Professor Emeritus of Science, Technology, and National Security Policy
Massachusetts Institute of Technology, March 3, 2018

Since before the early 1990s North Korea has been steadily building a capability in liquid propellant ballistic missile systems. The bulk of these systems are land-based and utilize Russian liquid propellant rocket motor and guidance technologies from the 1950s to late 1960s.

In addition to this stable of varied liquid propellant ballistic missiles, 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.

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 their source remains unknown in the public record.

The significance of the KN-11 is that North Korea will eventually be able to deploy submarine launched ballistic missiles that will have the capacity to attack South Korea and Japan from 360° of azimuth. This capability will completely eliminate even the speculative pretext that ballistic missile defenses will have any realistic capabilities against such North Korean missiles.

Even if the current ballistic missile defenses that the United States is building were to work as claimed, the need to defend against all azimuth ballistic missiles will require an extensive expansion of the number of detection and tracking radars in the defense-system. It will also require an even more extensive expansion of the number of interceptors and launch sites. Proliferated interceptor sites will be essential to place interceptors close enough to defended areas so as to allow them to achieve intercept points before the arrival of submarine-based ballistic missiles. The overall expansion of ballistic missile defenses required against all azimuth ballistic missile attack, both in theory and practice, will drive the cost of any defense system based on practical technologies well beyond anything that even the United States could afford.

The second worrisome area of North Korean ballistic missile development are liquid propellant ballistic missiles with ICBM ranges and payloads. North Korea has been developing liquid propellant ballistic missiles for nearly thirty years and their Russian-made components have been used with great ingenuity by North Korean rocket engineers. However, starting in mid-2017 North Korean ballistic missiles with ICBM ranges and payloads, and a variety of technologies needed to implement them, have appeared suddenly, as if from nowhere.

North Korean rocket engineers are unquestionably deeply knowledgeable about Russian rocket motors and related components, and they have demonstrated that they can creatively use these components and related 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 in the late 1980s and early 1990s.

Although the North Korean rocket engineering establishment today was initially established by Russian engineers and scientists, it is almost certain that by now it has many homegrown North Koreans who have absorbed

1 This short paper is the result of collaborations between the author, Theodore A. Postol and his colleagues, Dr. Ing. Markus Schiller, Dr. Ing. Robert Shmucker, and Dr. Richard L. Garwin. Most of the critical insights about North Korean ballistic missiles were derived in the collaborations with Schiller and Schmucker, who have a much deeper knowledge of these technologies than Postol. Similarly, the critical insights reported in this paper about a missile defense concept that could reliably defend the continental United States against North Korean ICBMs were derived with Garwin.

the innovative engineering culture brought by these Russian engineers.

A 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. The Nodong 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 an SA-5 variable thrust rocket motor for the SCUD-B motor that would normally be used in the SCUD airframe, it would have not 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 utilizes components from Russian rocket technologies.

THE ROCKET'S POWERED BY THE ENGINES

Figure 1 (on page 6) shows silhouettes of all the major liquid propellant ballistic missiles that have been demonstrated in tests up to the middle of 2016 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.

What is not shown in Figure 1 is the Hwasong-12, Hwasong-14, and the Hwasong-15 ballistic missiles that can carry significant payloads to much longer range than anything that North Korea had flown up to 2016.

As will be discussed later in this paper, North Korea suddenly took a gigantic step forward in 2017 with the introduction of these new long-range ballistic missiles. The appearance of which can be connected to the sudden and unpredicted entrance of an entirely new rocket motor, the Russian RD-250, which appeared as if it came from nowhere.

The first two silhouettes starting from the left of Figure 1 are the SCUD-B and C. The SCUD-D is almost certainly a close variant of the SCUD-C

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 tanks.

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.

Iraq's Al Hussein SCUD variant was a design modification of the SCUD-B that was somewhat similar in character to that of the SCUD-C. The Al Hussein was fabricated by increasing the volume by 20% of fuel and oxidizer tanks scavenged from disassembled SCUD-Bs and by modifying SCUD-B guidance systems that control pitch during the acceleration process. These modifications resulted in a missile that could achieve ranges of about 600 km with a 300 kg payload.

At the time of the Al Hussein's development Iraq, with help from European contractors, took several years to make this apparently minor modification of the SCUD-B. In the case of North Korea, it is clear that they have mastered the guidance and control technologies needed to make a wide range of adjustments to SCUD-B technology, and to the new and long-range missiles that suddenly appeared in 2017.

An important factor that makes it possible to make many SCUD-missile variants possible is that the SCUD-B motor is so reliable and well-designed that it can be expected to run for considerably more than 20 percent longer than its original required 62 seconds in the SCUD-B.

In all likelihood, North Korea's SCUD-B, SCUD-C,

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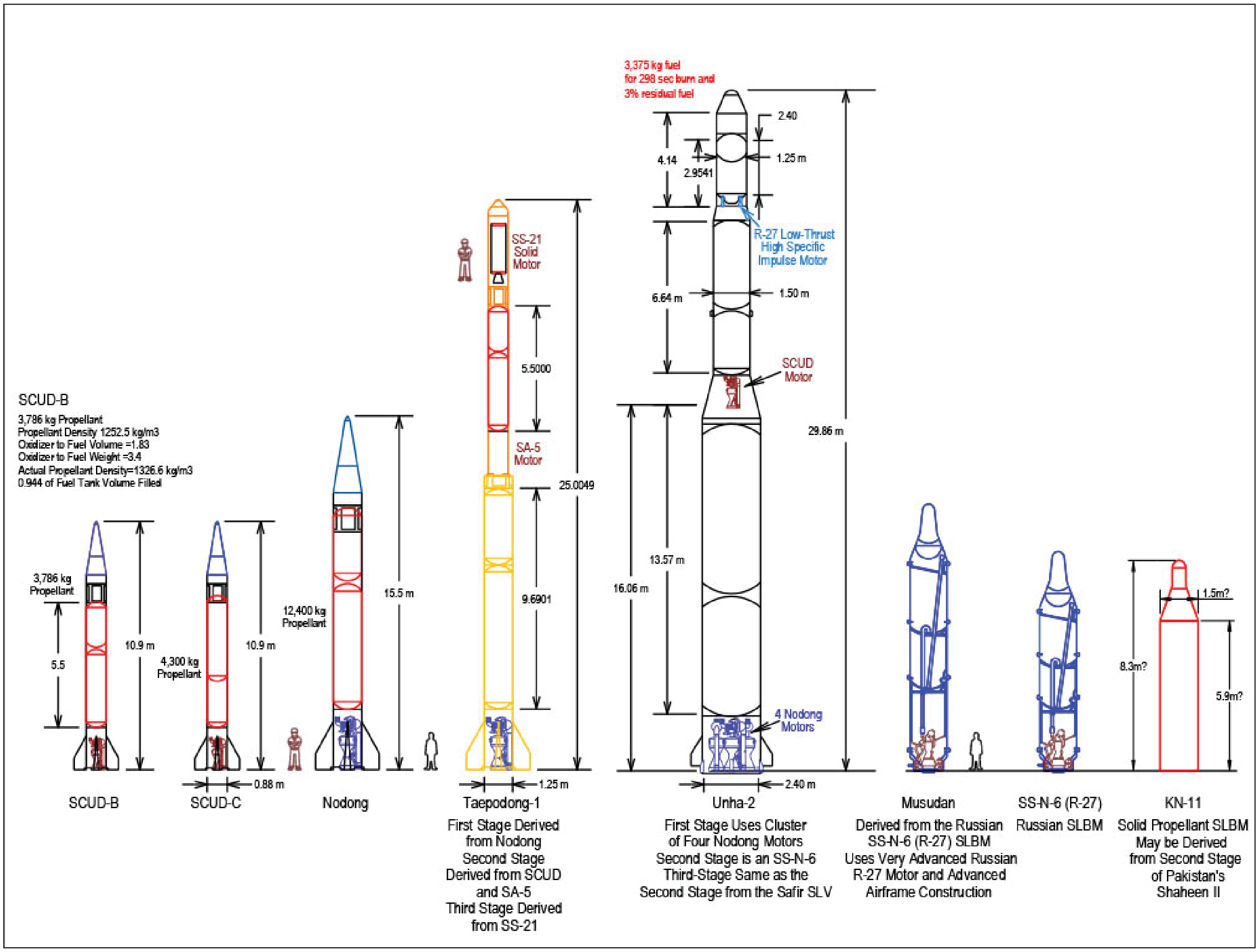
Figure 1



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 satellite 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.

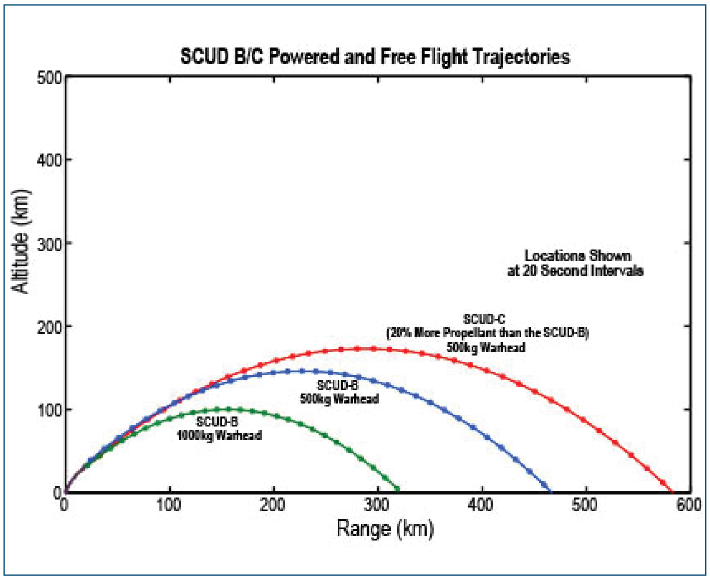
Figure 2 shows the trajectories and ranges that can be achieved by a SCUD-B with a 1000 kilogram warhead, and by a SCUD-B with a 500 kilograms warhead. As can be seen by inspecting the diagram, the SCUD-B could achieve a range of more than 450 kilometers with a 500 kilograms warhead if it was not aerodynamically 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 2, a SCUD-C with a 500 kilogram 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 with fuel and oxidizer tanks re-configured for lighter weight so as to achieve a 600 kilometer range with 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 1 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 exactly 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

Figure 2



those needed in rockets where it was first used. This 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 1 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 1 are of the North Korean Musudan and Russian R-27 SLBM (also known in the West as the SS-N-6). The R-27 vernier and main rocket motors burn a completely different Russian fuel and oxidizer combination relative to the propellants used in the SCUD-B and Nodong motors

The Musudan was only flown successfully once out of eight or nine attempts. However, the single successful launch of the Musudan indicated the availability to North Korea of a new class of rocket motors that use the storable high energy liquid propellant unsymmetrical dimethylhydrazine (UDMH) and nitrogen tetroxide (N_2O_4 are 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. The introduction of rocket motors that burn this high-energy propellant-oxidizer combination signaled a landmark advance in the capabilities of North Korean rocket systems.

The high-energy propellant R-27 vernier and main rocket motors in the Musudan made 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.

However, the use of this far more energetic fuel does not come without questions about potential operational limitations that could accompany the introduction of this fuel into a force of mobile North Korean rocket systems. 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 flexible in their applications as future mobile missile systems.

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

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 and other rocket motors relative to that of the SCUD-B and Nodong has profound implications for the capabilities of new North Korean rocket systems that utilize this much more energetic propellant.

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 while 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 are considerably higher.

Thus, the apparently relatively small extra specific impulse in the R-27 motor has major implications for rocket range and payload performance when motors with much higher specific impulses are available for use in new rocket systems.

THE MUSUDAN ROCKET

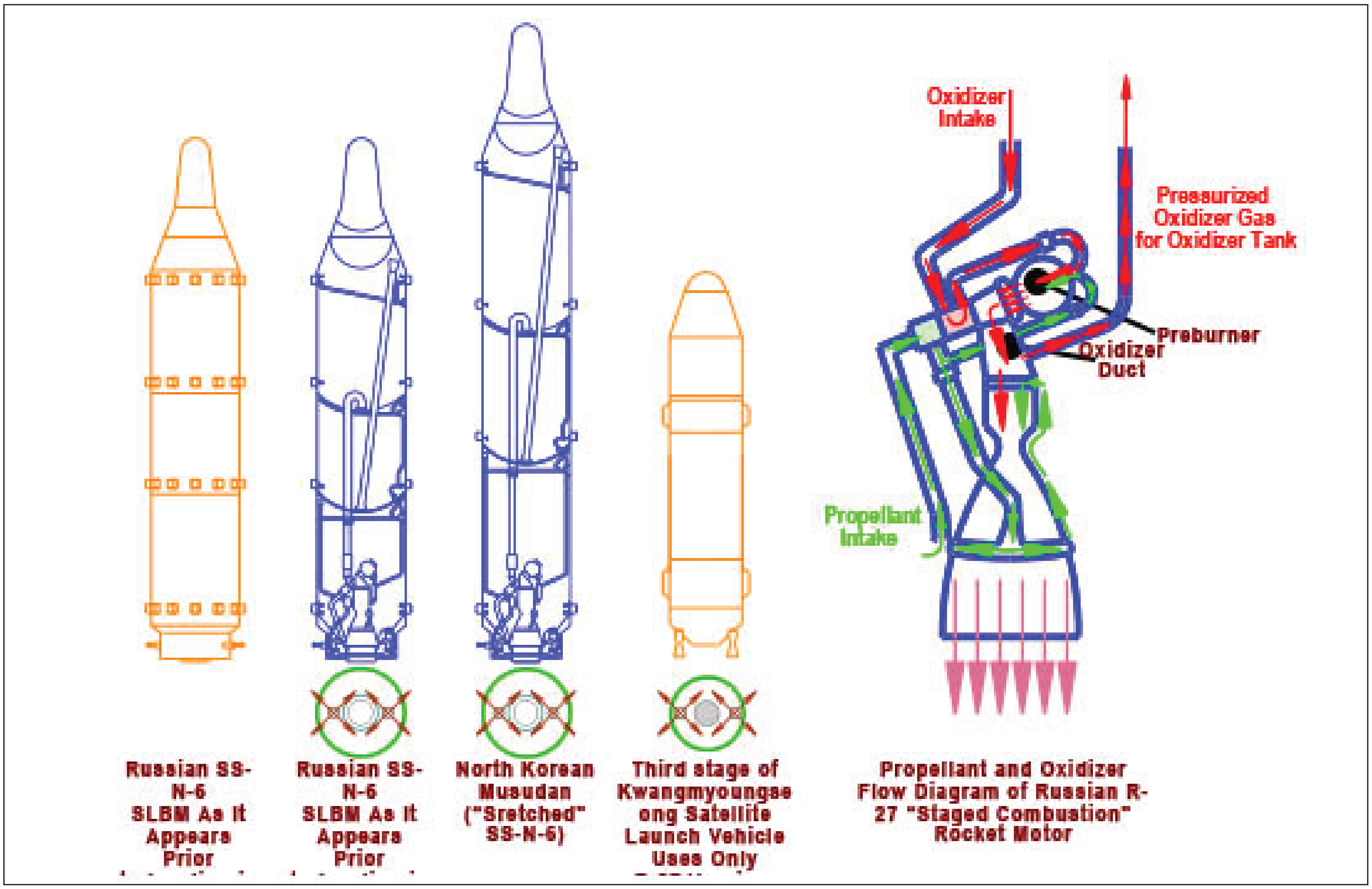
As already explained, the availability of more efficient rocket motors has benefits that are disproportionately higher than they actually appear by simply looking at the motor efficiencies alone.

The second silhouette from the left in Figure 3 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 that is connected to the bottom of the motor's nozzle. 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 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, a missile that was only displayed as a mockup in parades, was never flown, and had a configuration of multiple stages that would never be chosen by competent rocket design engineers. Yet in spite of of these glaring technical facts, the KN-08 was repeatedly misreported as a significant rocket development by major US news media (*the New York Times*), greatly adding to the general confusion about what was actually going on in the North Korean ballistic program.

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.

Figure 3



The right-most silhouette in Figure 3 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 pressurized and heated oxidizer and a small amount of combustion products. The pressurized hot oxidizer then passes through the turbine that drives the fuel and oxidizer turbopumps. The oxidizer then passes through the turbine into an oxidizer duct that delivers it directly into the combustion chamber where it is mixed with the heated fuel. Thus, the process of injecting the heated oxidizer from the preburner into the oxidizer duct is accompanied by the extraction of mechanical energy that is then used to drive the propellant and oxidizer turbo pumps that suck the fuel into the engine

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 3 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 3) 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 rockets 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 3 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 indicated 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 had 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, in spite of these advances, it is 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 faced in its efforts to extend the airframe of an SS-N-6 were quite substantial, and its ability to meet the exceptional manufacturing challenges posed by the Musudan's integrated airframe and propulsion system are likely reflected its flight-test record.

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 4.

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.

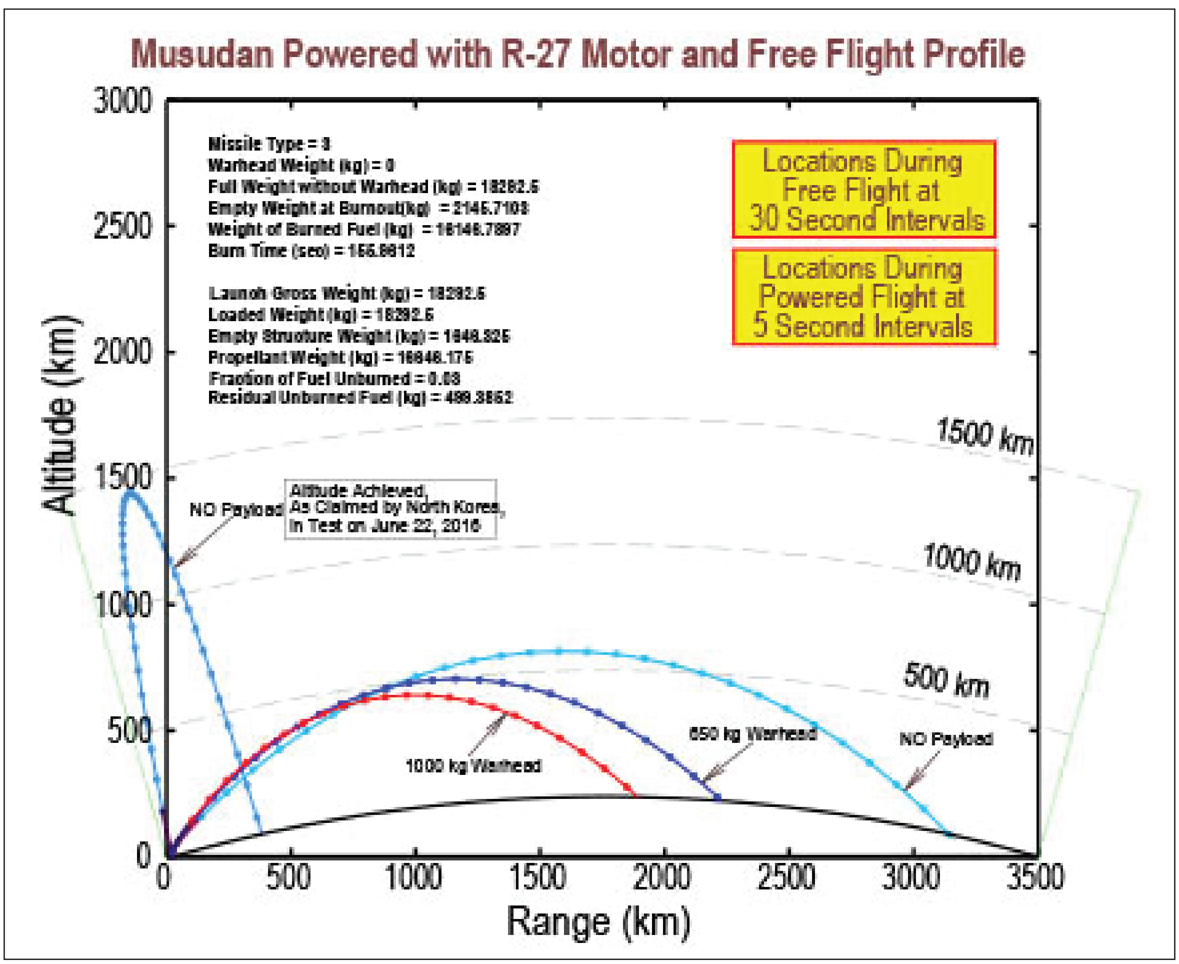
Simulations of the observed June 23 test trajectory can be used to verify a rough model of the Musudan missile.

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 range, but it is much shorter than the 4000 km range that was widely 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 already noted, the R-27 nitrogen tetroxide oxidizer

Figure 4



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. In addition 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 will require that its fuel and propellant be transported separately in temperature-controlled containers along with any land-mobile missile (in this case, the Musudan) that uses this propellant. However, controlling the temperature of the transported liquid oxidizer before it is loaded into the missile might not be adequate by itself. It may also require that the mobile missile be temperature controlled as well.

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 sit inside the fuel tank and are 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.

In the end, it appears that the Musudan project must be judged as a failure of the North Korean missile establishment. The reasons for this can be based on informed speculation.

The Musudan design is based on the Russian R-27 (SS-N-6) submarine launched ballistic missile. This missile was a masterpiece design of Russian rocket engineering. The rocket motor was immersed inside the fuel tank so as to keep the length of the rocket short so it could carry more propellant while confined to the launch tube of a submarine. The ability to immerse a rocket motor inside a rocket-fuel tank demands extraordinary quality control in manufacturing. Even the most minor leaks or problems with the strength of welds will result in a catastrophic failure of the rocket during flight. The test record of the Musudan suggests that the problems of implementing extraordinarily high levels of quality control in manufacturing might well have been beyond that of the North Korean rocket-making establishment. This possibility would certainly explain a single successful test flight among many failures. The single spectacularly successful flight in the test program, followed by other failures, suggests that the basic design was workable but its implementation was beyond the capability of North Korean manufacturing capacities.

It has been repeatedly suggested (again in *New York Times* articles) that the high failure rate of the Musudan was the result of an American secret program to sabotage the Musudan flights through the introduction of computer viruses by the US through some kind of imagined scheme. This claim has been repeated often in the *Times* and raises the most serious questions about the technical literacy of both the writers and editors at the *Times*. It appears that nobody on the *Times* staff recognized that a missile must actually have a control computer if it is to be destroyed by the introduction of a fatal virus. The Musudan is essentially controlled by servo-mechanical systems and does not have a control computer as imagined by the *New York Times* writers.

The more important issue raised by such technically illiterate claims that have permeated *Times* reporting on the North Korean ballistic missile program is how the editorial oversight of the newspaper could have repeatedly failed to correct such an overtly silly and embarrassing claim.

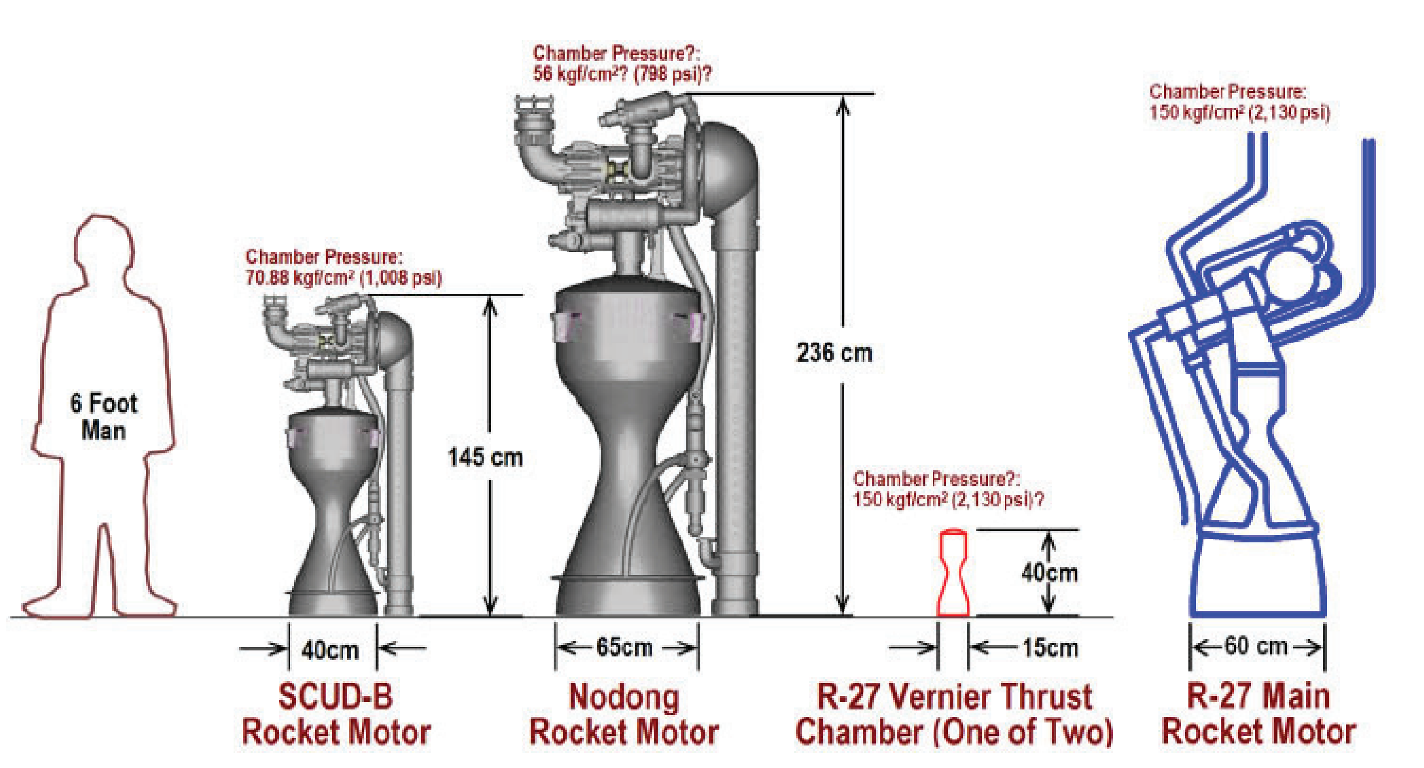
NORTH KOREA'S HERITAGE OF RUSSIAN LIQUID ROCKET MOTORS

Figure 5 on the next page shows the four Russian-built liquid propellant rocket engines that have been the critical components in essentially all of North Korea's liquid propellant ballistic missiles and satellite launch vehicles up until 2017. The only new rocket system used in the period up to 2016 that did not use Russian liquid propellant motors is the newly emerging KN-11 solid-propellant submarine launched ballistic 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 launch vehicle. The R-27 vernier motors (fourth from the right 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.

Figure 5



Once the engine designs were frozen, the project was transferred 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 6) 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.

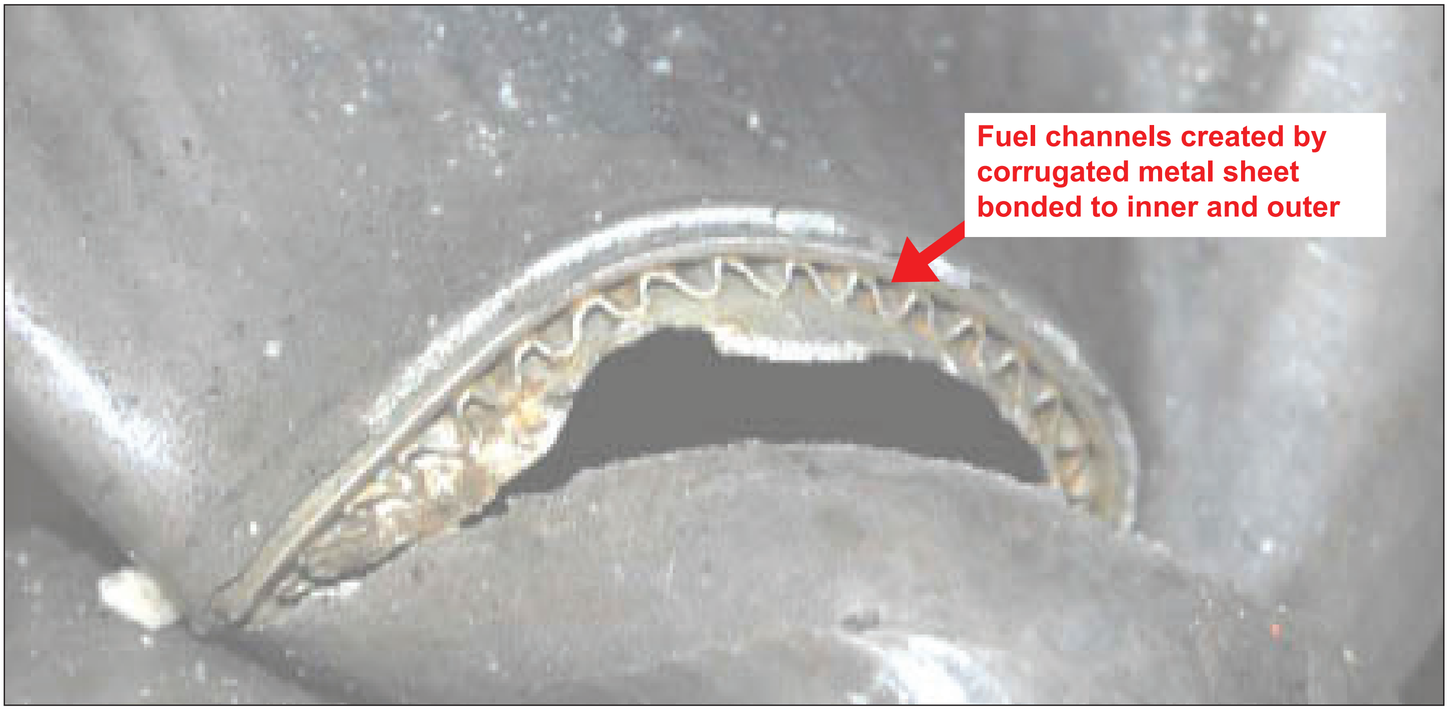
The SCUD-B rocket motor generates about 13.3 tons of thrust at sea level and the Nodong generates about twice the thrust of the SCUD-B (28 to 29 tons at sea level). (Note: all tons in this essay are metric tonnes). The R-27 main rocket motor in combination with its verniers also generates about 27 tons 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 3500 kilogram force of thrust at sea level and the same thrust at high altitude when the nozzle has been extended.

THE BEGINNING OF THE NORTH KOREAN MISSILE DEVELOPMENT "BREAKOUT" OF 2017

On May 14, 2017 a single stage rocket called the Hwasong-12 flew a lofted trajectory that reached 2111 km that fell 787 km east of North Korea in the Sea of Japan. This rocket was powered by a main engine that had a single thrust-chamber and four vernier motors. Unknown at the time of its launch, the Hwasong-12 was the first test of the first stage of a new two-stage rocket that would ultimately be known as the Hwasong-14.

By July 3, 2017, while Americans were preparing for the 241st celebration of the Declaration of Independence, yet another new rocket was launched by North Korea. This

Figure 6



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.

rocket had two stages and was also flown on a near-vertical trajectory. After five to six minutes of powered flight, the second stage of the missile shut down and coasted to an altitude of about 2,720 kilometers. It then fell back to Earth, reentering the atmosphere above the Sea of Japan some 900 kilometers to the east of where it had been launched. The rocket's upper stage coasted in freefall for about 32 minutes, and the overall time-of-flight, from launch to atmospheric reentry, was about 37 minutes. The launch occurred at 8:39 p.m., United States' Eastern Time. Within hours, the news of the launch was trumpeted by the US mainstream press: North Korea had flown an intercontinental ballistic missile (ICBM), the Hwasong-14, a missile that could carry nuclear warheads to Anchorage, Alaska, and to the continental United States as well!

Only three and a half weeks later, on July 28, there was a second launch of the Hwasong-14, this time at night, Korean time. The rocket flew approximately the same powered flight trajectory that it had on July 3 (or July 4 in North Korea), however, this time it reached a higher altitude—a reported 3,725 kilometers. This longer flight path led to yet more unwarranted conclusions that the continental United States was now directly under threat of nuclear attack by North Korea. Actually, however, in this second case, by our calculations, the second stage of the so-called ICBM carried an even smaller payload and tumbled into the atmosphere at night over the Sea of Japan. The spectacular night-reentry of the rocket—what was almost certainly the heavy front-end of a nearly empty upper stage—created an impressive meteoric display that some observers incorrectly claimed was the breakup of a failed warhead reentry vehicle.

Like any missile system, the actual lift and range capability of the Hwasong-14 depends on many technical details. Among these are the type of fuel burned by the missile, the efficiency of its rocket motors, the total amount of propellant carried in each stage, the weight of the missile's airframe, and the weight of different components, including rocket motors, plumbing, guidance and control systems, and the like.

In the case of the Hwasong-14, almost all of the critical parameters that ultimately determined the rocket's ability to carry a payload-weight to a given range could be deduced, with some uncertainties, from photographs, videos of its initial powered flight, engineering knowledge of rocket systems, and specific other engineering information that can be determined by other observations of the missile and its motor components.

For example, the performance characteristics of the main rocket motor that powers the first stage are well known. This is in part because the rocket motor has been unambiguously identified as derived from components of a well-known family of Russian rocket motors. The type of propellant used by this family of motors is also known—unsymmetrical dimethylhydrazine (UDMH) and nitrogen tetroxide (NTO), a highly energetic propellant combination used extensively in Russian rocket systems.

The dimensions of the Hwasong-14 are readily determined from photographs of the missile and its length, as measured relative to the known length of the Chinese-made vehicle that carries it. Since the density of the propellant is known, and the dimensions of the rocket stages and the functions of the different sections of the rocket stages are easily identified, very good estimates of the weights of the stages, airframes and rocket motors can be deduced from simple volumetric analysis and knowledge of design features. Although many of the refined details of the rocket may not be known, the general information of the type described above provides quite good estimates of how well the rocket will perform.

These data lead to an overall weight estimate of roughly 37 metric tons for the Hwasong-14. The known characteristics of the main first-stage rocket motor, and the observed rate of acceleration of the rocket at launch, result in a highly constrained check on the missile model we created to estimate its overall range and payload performance.

One critical parameter of the Hwasong-14 is not yet known with certainty: the exact powered flight time of the second stage. This parameter is an important factor in determining the overall performance of the Hwasong-14, due to a phenomenon known among rocket engineers as "gravitational losses" during powered flight. To perhaps oversimplify the physics involved, the longer the rocket motor burns against the gravitational pull of the Earth, the less efficiently it accelerates its payload to a final speed. But two articles in *The Diplomat* magazine reported flight times for the second stages of the rockets that North Korea launched in July. Two independent sources have confirmed those times to us as accurate.

Figure 7 shows photographs extracted from North Korean videos of the launches of the Hwasong-14 missile during the morning of July 4 (in North Korea; the evening of July 3 in the United States) and during the night-launch on July 28. Careful examination shows that the first stage of the Hwasong-14 is powered by a large single rocket motor supported by 4 small "vernier" motors that add to the main thrust and are used to change the direction of the rocket during powered flight and to maintain its vertical stability during its initial lift-off and vertical acceleration. North Korea has also released videos of tests of the Hwasong-14 rocket motor (shown firing on a test stand in Figure 8).

THE GAME CHANGER – THE RUSSIAN RD-250 ROCKET MOTOR

The rocket motor used in the Hwasong-12 and 14 has been identified as derived from a family of Russian rocket motors known as the RD-250 or RD-251. The original motors used six thrust chambers fed by three turbo pumps to together generate roughly about 240 tons (about 530,000 pounds) of lift.

The North Koreans may have obtained this motor along with many others as part of a vast shipment of rocket components to North Korea that occurred in the late 1980s and early 1990s during the simultaneous disintegration of the national economy and political system of the Soviet Union. Until recently, almost all of the liquid-propellant motors seen in North Korea's rockets could be traced back to the Makayev Institute, a vast and highly capable organization that was responsible for the design of all types of Soviet ballistic missiles. Because of the prominent role of Makayev in Soviet ballistic missile production, this institute would have had large numbers of rocket motors in storage that were used to build various models of SCUDs and the SS-N-6 submarine-launched ballistic missile (aka R-27) used on Russian Yankee class submarines.

The newest Russian rocket motor now identified in the North Korean arsenal, derived from the RD-250/251 and used in the Hwasong-14, is not from the Makayev Institute, but from an entirely different major rocket motor manufacturer, NPO Energomash, which supported the OKB-456 Design Bureau in the Soviet Union. This rocket motor was associated with rocket and space launch vehicles produced in Ukraine. The presence of RD-250/251 rocket components in a new North Korean rocket raises new and potentially ominous questions about the variety and extent to which Soviet rocket motors might have been obtained by North Korea during the collapse of the Soviet Union.

An image of the original RD 250/251 rocket engine can be seen in the image on the left in Figure 9.

The skill needed by North Korean engineers to adapt components from the powerful RD 250/251 rocket motor for their own purposes can be appreciated by examining Figure 9.

Figure 7

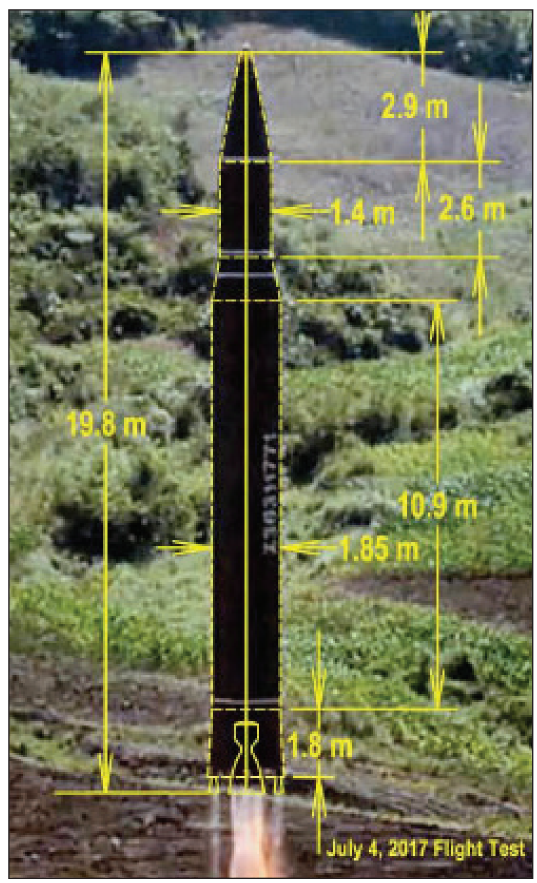
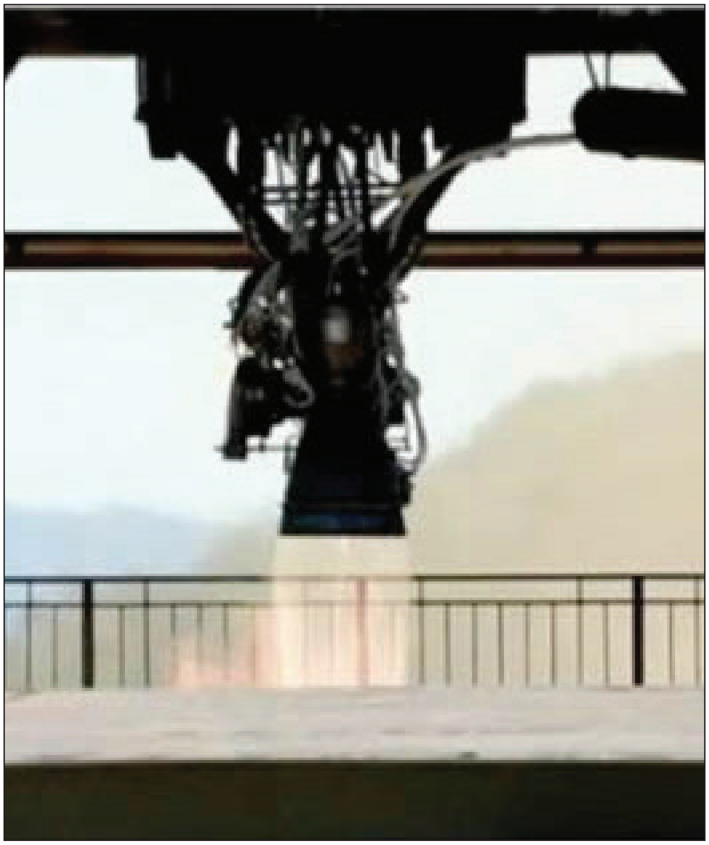


Figure 8



The original RD 250/251 was a rocket motor that consisted of six thrust chambers, driven by three powerful turbo pumps. The rocket motor used in the Hwasong-12 and Hwasong-14 uses a single turbopump from the RD 250 to drive a single thrust chamber from the RD 250 in addition to four vernier rocket motors.

Each of the three turbo pumps in the original rocket engine was nested between two thrust chambers, at a height below the combustion chamber and above the gas exhaust nozzle of each thrust chamber. This clever design made it possible to shorten the length of the rocket motor compartment and to reduce the overall length and weight of the first stage of a rocket.

The image on the right in Figure 9 is an enlargement taken from Figure 8, a photo of the Hwasong-14 rocket motor firing on a test stand. The outline of the motor's thrust chamber is shown in a silhouette overlay and the location of the turbopump next to the single thrust chamber is shown to be exactly at the height of the turbopump in the RD 250/251 motor complex. It is clear that the final rocket motor mounted in the Hwasong-14 has this single powerful turbopump feeding propellant to both the main rocket motor and the four smaller vernier motors used to control the direction of the missile.

The design indicates a well-thought-out approach to a completely new missile that was not seen in public until the launch of the Hwasong-12, which was essentially a test aimed at proving the functionality of the first stage of the two-stage Hwasong-14. It is a remarkable achievement in itself that North Korea has been able to master the use of these components well enough to be able to adapt them to their special purposes.

We have determined that the approximate properties of the Hwasong-14 missile, with a second stage upgraded with more capable vernier motors from the Russian R-27 missile, will be as follows:

First Stage[a]

weight (kg)	Structure[b] Factor	Thrust at Sea Level in Kilogram force (kgf)	Specific Impulse at Sea Level (sec)	Thrust in Vacumn (kgf)	Specific Impulse in Vacumn (sec)	Burn Time (Seconds)
33,370	0.10	51,000	260	54,000	290	150

Second Stage[b]

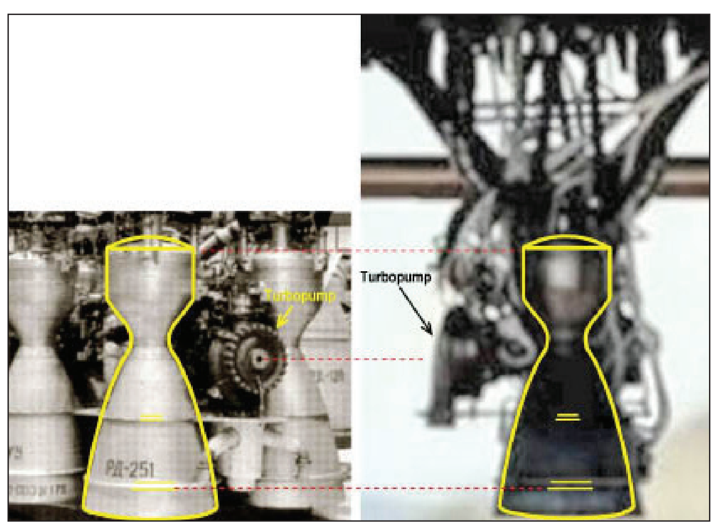
weight (kg)	Structure[b] Factor	Thrust in Vacumn (kgf)	Specific Impulse in Vacumn (sec)	Burn Time[c] (Seconds)
3500	0.14	7000	300	135

a. There is some chance that the oxidizer used in either or both rocket stages is a mix of inhibited red fuming nitric acid (IRNFA) and nitrogen tetroxide (NTO) or possibly only IRNFA.

b. These structure factors include our assumption that the propellant reserves for both stages at burnout is 3%.

c. The burn time cited here is for the assumption that the second stage uses vernier rocket motors similar to those used on the upper stage of the Iranian Safir and North Korean Unha-3 SLV's. This leads to higher payloads relative to those that would be achieved using motors with longer burn times. There is a good chance that the second stage uses four vernier motors comparable to the R-27/SS-N-6 in size, but capable of throttling down to 20% thrust. This would allow for precise injection of a very small satellite and explain the long burn time numbers-assuming the original purpose of the rocket was to launch small satellites into orbit. As noted in the text, the published numbers for the second stage burn times are 224 and 233 seconds. These alternative burn tiimes should be used to calculate the range-payload capacity of the rocket assuming the published powered flight times are correct.

Figure 9



THE END RESULT OF THE NORTH KOREAN "BREAKOUT" OF 2017—A TRUE ICBM

On Tuesday, November 28, 2017, North Korea launched a missile called the Hwasong-15. Our preliminary analysis of the now substantial publicly available data indicates that the second stage of the Hwasong-15 has characteristics that are very close to that of the second stage of the SS-11 Soviet ICBM.

This extraordinary development means that the Hwasong-15 has the payload to range to deliver relatively heavy first-generation atomic weapons to the continental United States. It also should have sufficient excess payload to carry simple countermeasures that would readily defeat the Ground-Based Missile defense (GMD) system.

The analysis of the Hwasong-15 presented herein is based on a preliminary analysis, but we have received multiple confirmations that the results of this assessment are very close to those produced by the US government. There are many details of its design that still need to be resolved in follow-on studies, but the basic features of the Hwasong-15 that will be summarized in this section define the general capabilities of this new missile.

These general capabilities are as follows:

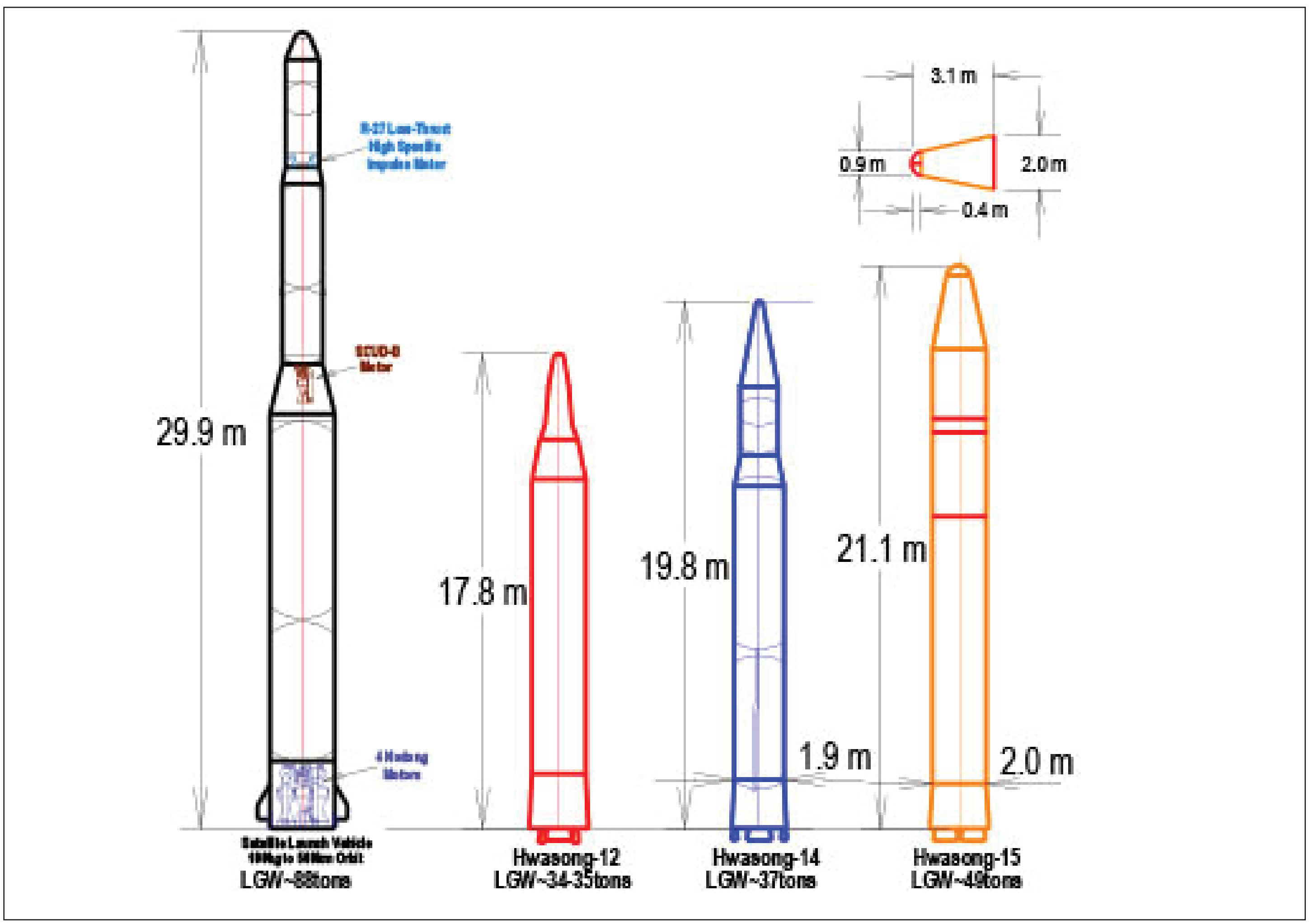
1. The Hwasong-15 should be able to deliver a payload of about 800 to 850 kilograms to Washington, DC, and larger payloads to US cities that are at shorter ranges from North Korea.

   For example, the Hwasong-15 could potentially deliver a payload of 1300 kg to Hawaii, 1200 kg to Seattle, and 1000 kg to Los Angeles

2. About 25% (more or less) of the total weight of a nuclear-armed reentry vehicle is used to protect the atomic device from the extreme deceleration forces (about 60 G's at full range) and heating rates that occur during atmospheric reentry.

   Since the Hwasong-15 is in theory capable of delivering a payload to Washington DC of 800 to 850 kg, it could deliver a nuclear weapon to Washington that weighs about 600 to 650 kg. However, the nuclear warhead would have to be able to survive prodigious reentry deceleration forces of about 60 G's.

3. Simple balloon decoys that would overwhelm the GMD with credible targets could weigh significantly less than a kilogram each, even including the weight of a balloon



deployment system. Thus, as long as the North Korean Hwasong-15 has several tens of kilograms of payload to spare, it will be capable of completely overwhelming the US GMD system by deploying many tens of credible decoys against it.

4. There is a defense concept that has been extensively developed by Richard Garwin and Ted Postol that could be used to defend the continental US, by destroying ICBMs launched from North Korea, like the Hwasong-15, before they end their powered flight and can deploy countermeasures to the GMD. As will be shown shortly, this concept, if implemented properly, would be highly effective against the Hwasong-15 and other similar long-range missiles. In particular, the Hwasong-15 has a 300 second powered flight time, which is ample for engaging the missile before it ends powered flight .

What is unknown at this time is how much Soviet Cold War era ICBM equipment is available to North Korea and to what extent North Korea could build an arsenal of Hwasong-15 and related missiles.

This development also indicates that economic sanctions against North Korea have had little if any adverse affects on its ballistic missile programs. This observation has nothing to do with the analysis provided herein, but it is noted because of its important policy implications.

ANALYTICAL FINDINGS

The only way North Korea could have produced the Hwasong-15 so soon after showing the world the Hwasong-14 is if Hwasong-15 missile was being developed in parallel to the Hwasong-14.

The Hwasong-15 shows astonishing technical advances over the Hwasong-14. The first stage uses a full RD-250 rocket motor unit that has two thrust chambers driven by a single turbopump. This motor delivers about 80 tons of thrust at sea-level. The thrust chambers on the Hwasong-15 first stage are mounted on gimbals, which eliminates the need for vernier control engines. The removal of vernier control engines reduces the overall deadweight of the missile and when properly implemented increases overall reliability. The reduction in deadweight frees up weight for the final payload.

However, the most astonishing feature of this missile is its second stage.

The second stage is much too large and heavy to be powered by the 3.5 ton thrust R-27 vernier rocket motors that are likely being used in the second stage of the Hwasong-14. The second stage of the Hwasong-15 is also too large and heavy to be powered by a pair of 3.5 ton thrust R-27 rocket motors. A careful analysis of the physical dimensions of the upper stage, and the overall weight of the vehicle as determined by measurements of its acceleration at liftoff, leads to the conclusion that the second stage is nothing like what has been seen before in North Korea.

In what follows we show that the evidence is overwhelming that the characteristics of the second stage of the Hwasong-15 are very close to that of the second stage of the Soviet SS-11 ICBM, which first appeared in the Soviet strategic arsenal around 1960.

The SS-11 was a workhorse system for the early Soviet strategic arsenal and there is little doubt that a very large number of SS-11 first and second stage rocket components (including motors) were produced when the SS-11 was first deployed. In addition, the SS-11 was in service for roughly 40 years and its components might well have been included in the gigantic transfer of rocket motors from Russia to North Korea that probably occurred in the early 1990s while Russia was in a near total political and economic collapse. It also cannot be ruled out that these technologies were transferred at a later time, as suggested by Michael Elleman of the IISS.[1] Whatever the source of this technology, it appears nearly certain that the upper rocket stage on the Hwasong-15 is a direct descendant from one of the many SS-11 variants that were developed and experimented with by the Soviet Union during the Cold War.

Figure 10 on the next page shows a silhouette of the Hwasong-14 next to a silhouette of the Hwasong-15. The dimensions of the Hwasong-15 were derived from careful analysis of photographs of the rocket on its transporter vehicle. The diameters of the first and second stages of the SS-11 are the same as that of the Hwasong-15 (2 m). Also shown in Figure 10 is a line drawing in bright green of the silhouette of the second stage of the SS-11. A quick inspection of the diagram shows that the dimensions of the SS-11 second stage and the second stage of the Hwasong-15 are close to the same.

The figure on the left shows the Hwasong-14 during its nighttime launch on July 28, 2017 and the figure on the right shows the Hwasong-15 immediately prior to its launch on November 28, 2017. The line drawing in bright green shows the silhouette of the SS-11 second stage adjusted on the same dimensional scale of the Hwasong-14 and Hwasong-15. It is clear that the SS-11 second stage has essentially the same dimensions as the second stage of the Hwasong-15.

Figure 11 shows a video frame of the upper stage of the Hwasong-15 during its early powered flight. Because the light from the rocket plume is a good illuminator of the missile, one can see more details of the upper stage. As inspection of the diagrams show, the silhouette of the upper stage of the SS-11 very closely matches the upper stage of the Hwasong-15.

The inset on the far right of Figure 11 shows a drawing from the Russian website (http://ru-abandoned.livejournal.com/1166627.html) that discusses engineering details of the retired SS-11 ICBM. The internal geometry of the second

1 See, Michael Elleman, The secret to North Korea's ICBM success, 14 August 2017 https://www.iiss.org/en/iiss%20voices/blogsections/iiss-voices-2017-adeb/august-2b48/north-korea-icbm-success-3abb

stage rocket motor is shown clearly, and it can be seen to have dimensions that are essentially the same as those of the second stage on the Hwasong-15.

The four insets on the next page that comprise Figure 11 show how closely the upper stage of the SS-11 (the inset on the far right) matches the dimensions of the upper stage of the Hwasong-15. The rocket motors attached to the center part of the stage are used to accelerate the second stage as it separates from the first stage. The acceleration from these motors force propellant and oxidizer into the rocket motor turbopump so as to assure a smooth movement of fluid into the rocket motor as the motor starts. Note that apparently similar rocket motors can be seen essentially at the same location in both the Hwasong-15 and SS-11 second stages.

Figure 12 and Figure 13 show the consequences of an SS-11 second stage on the Hwasong-15.

Up until now, some analysts (including me) have assumed that the upper stage of the Hwasong-15 would be powered by a pair of vernier motors from the Russian R-27 SLBM.

As shown in Figure 3 (near the beginning of this article), the original R-27 (SS-N-6) had a single small turbopump dedicated to driving two thrust chambers that form a straight line with the main rocket motor. These two thrust chambers and turbopump generate about 3.5 tons of thrust and in combination control the rotation, pitch and yaw of the R-27 during its powered flight.

Figure 10

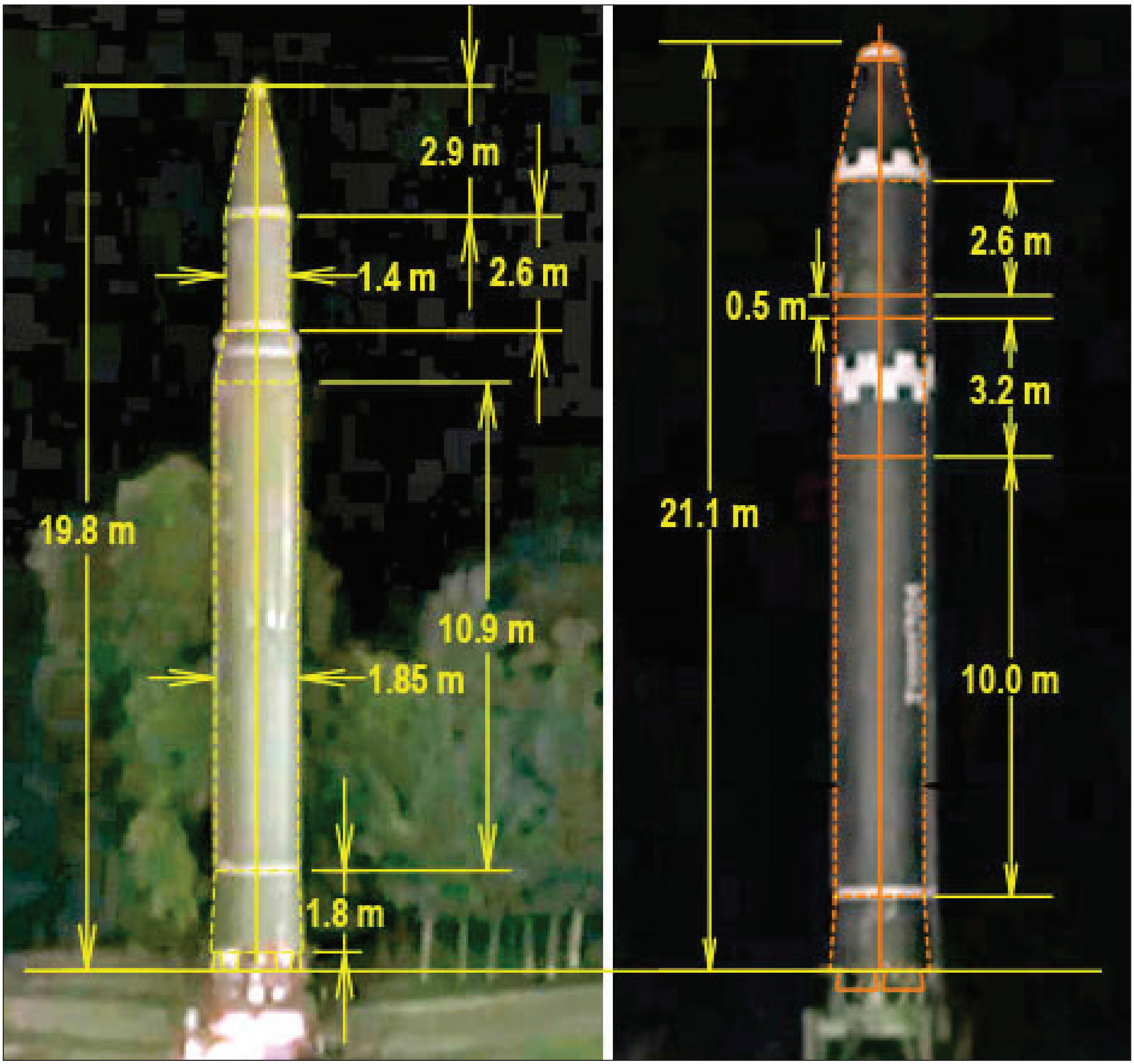
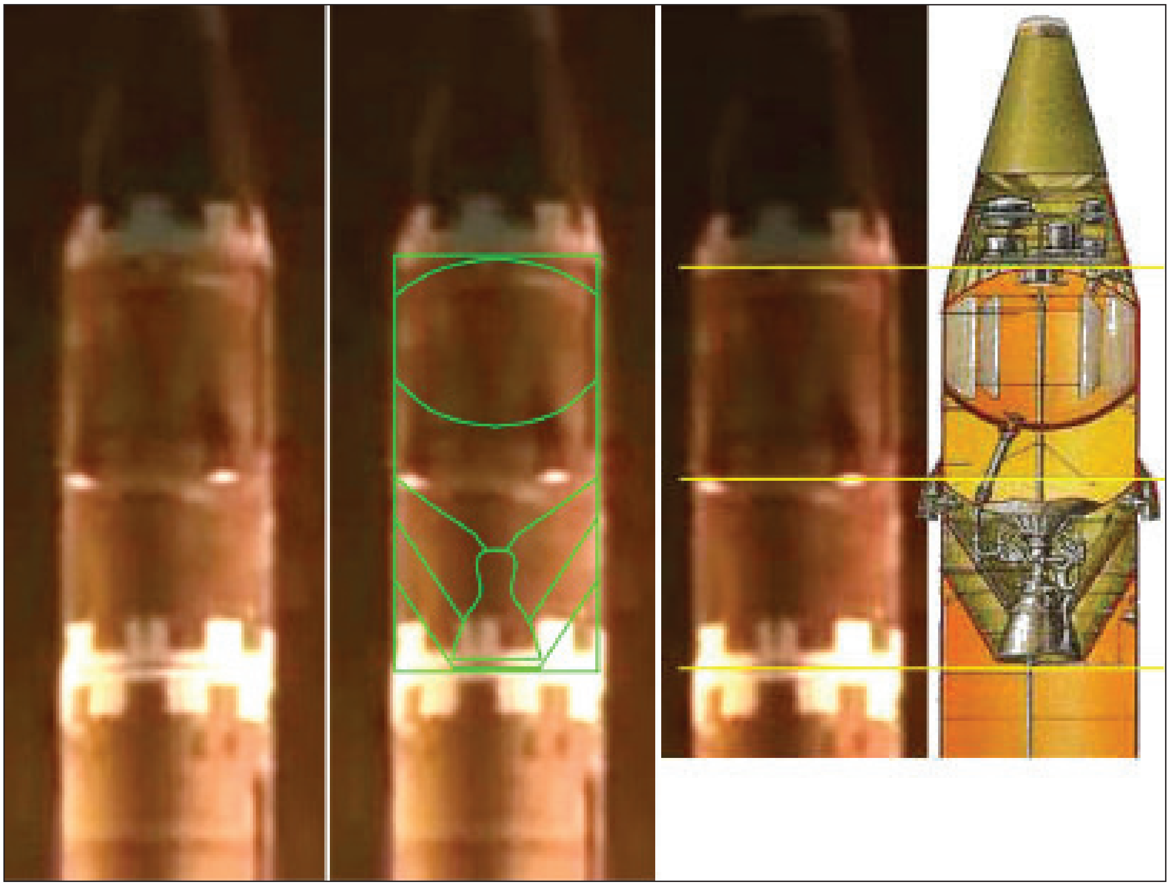


Figure 11



The Hwasong-14 appears to have used the single turbopump and accompanying pair of R-27 thrust chambers for its second stage. Our analyses, and the analyses of others, have shown that much improved second stage performance could be achieved in the Hwasong-14 if two turbopumps and four verniers were used in its second stage.

Initial performance calculations for the Hwasong-15 show that such a combination of R-27 thrust chambers would not be capable of driving a second stage as large and heavy as that of the Hwasong-15. This observation alone indicates that the Hwasong-15 second stage uses a higher thrust propulsion system.

If the second stage were instead powered with R-27 vernier thrust chambers it would be underpowered and would need to have a second stage that is lighter by a factor of roughly 2 relative to the second stage we see on the actual Hwasong-15. The only way the second stage could be heavier and properly matched to give maximum weight-to-range would be if it had a considerably higher thrust. This is exactly the thrust we see in the SS-11 stage used in the Hwasong-15.

Those individuals who have access to classified information can readily confirm from measurements of the powered flight time of the upper stage whether the upper stage is an indigenous stage using four thrust chambers from the R-27 or the more efficient propulsion system from the SS-11.

Simulations of the two variants of the Hwasong-15 discussed above indicate that if the second stage is in fact from the SS-11, the intelligence community should have observed a second stage powered flight time of about 180 to perhaps 184 seconds.

It therefore seems nearly inescapable that second stage of the Hwasong-15 is either from an SS-11 or very closely related to the upper stage of the SS-11.

WHAT DOES ALL THIS MEAN?

The technical meaning of this astonishing North Korean development is that the Hwasong-15 can carry a considerably larger payload to ICBM ranges than any previous rocket systems observed in the arsenal of North Korea. A rough estimate of its range versus payload capabilities is shown in the graph labeled Figure 12

The graph above shows rough estimates of the payload versus range of the Hwasong-15 assuming it has an upper stage roughly similar to that of the SS-11 Soviet ICBM, with its much higher thrust and more efficient rocket motor. As can be seen from an inspection of the graph, the Hwasong-15 design with an SS-11-Class upper rocket stage can deliver about 850 kg to Washington DC. Assuming roughly 20% of the total weight of a warhead is heat-shield and physical structure; this means that North Korea will have to be able to build a nuclear weapon that weighs no more than about 650 kg if it is to threaten Washington with a nuclear attack delivered by a Hwasong-15. In addition to this weight limitation, North

Figure 12

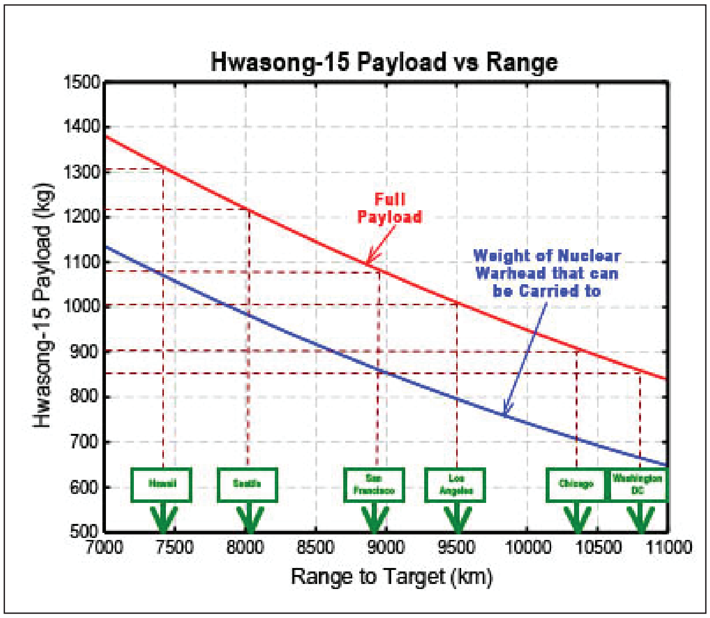
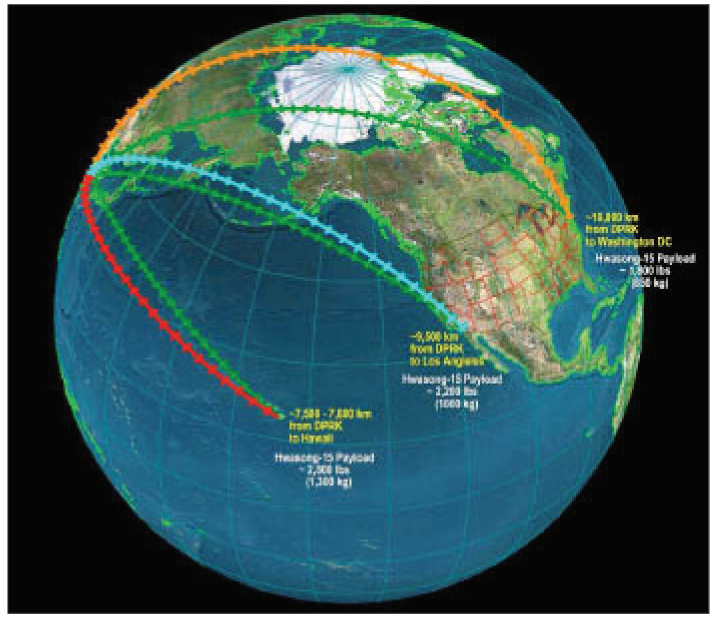


Figure 13



Korea would also have to be able to build a nuclear weapon that could survive a 60 G reentry deceleration at the target.

Figure 13 simply illustrates the graphical information summarized in figure 12.

A second important insight, which is more of an observation for policymakers, is that in spite of the extremely severe sanctions on North Korea, it has somehow managed to either obtain new rocket technologies or expand its existing capabilities considerably. The reasons for this are unknown to this author, but the facts are clear.

North Korea has developed shorter range solid propellant rockets as well as more advanced liquid propellant rockets in spite of the severe economic sanctions brought against it. This is not an issue for debate in this paper, but it is worthy of note for those who are concerned with questions of how to influence North Korea's behavior.

Figure 14 is a table that summarizes an approximate estimate of the characteristics of the Hwasong-15 first and second stages. Although this model of the Hwasong-15 might eventually be revised relative to the numbers in the table below, we believe that these parameters are adequate for a preliminary assessment of the range and payload capabilities of the Hwasong-15.

Figure 15 shows the powered and free flight trajectory of the Hwasong-15 on a trajectory where a launch is postulated at Pyongyang and an impact is postulated on Washington DC. As can be seen from Figure 15, the powered flight phase the Hwasong-15 is quite short relative to that of the free flight

Figure 14

First Stage[a]

Weight (kg)	Structure[b] Factor	Thrust at Sea Level (kgf)	Specific Impulse at Sea Level (sec)	Thrust In Vacuum (kgf)	Specific Impulse in Vacuum (sec)	Burn Time (Seconds))
41,800	0.10	80,000	269	89,500	301	115

Second Stage

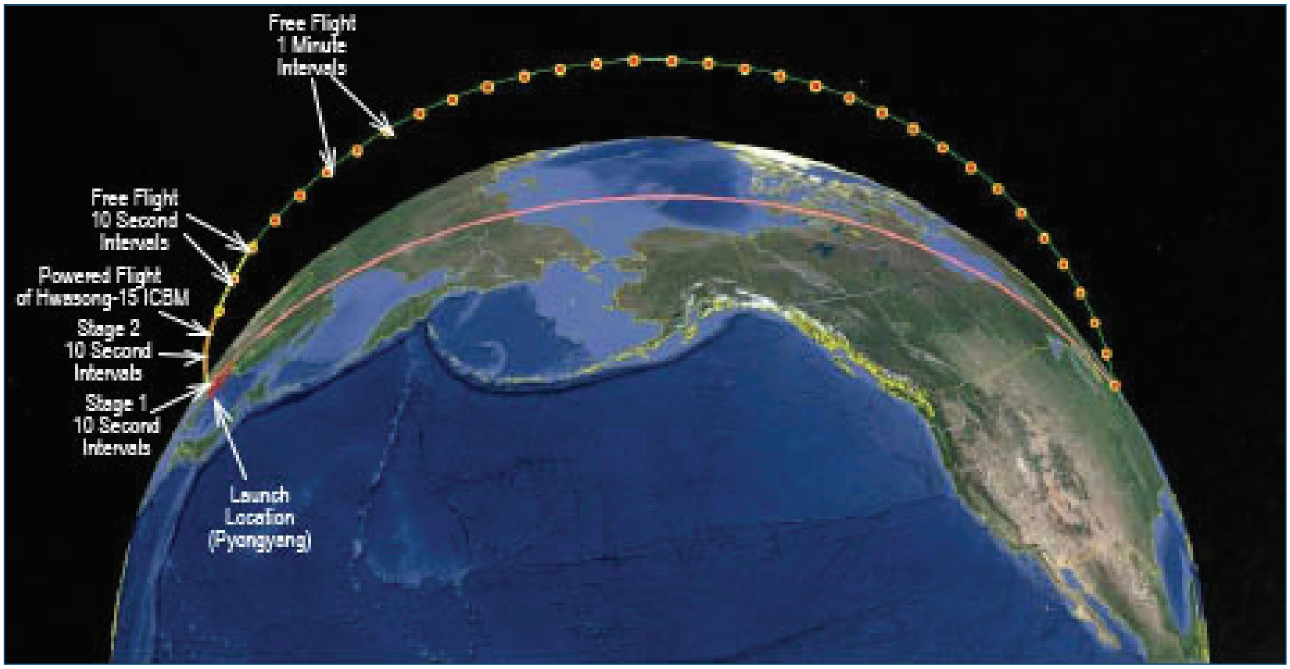
Weight (kg)	Structure[b] Factor	Thrust In Vacuum (kgf)	Specific Impulse in Vacuum (sec)	Burn Time[c] (Seconds)
9,100	0.12	13,400	325	184

a. There is some chance that the oxidizer used in the first stage is a mix of inhibited red fuming nitric acid (IRNFA) and nitrogen tetroxide (NTO) or possibly only IRNFA.

b. These structure factors include our assumption that the propellant reserves for both stages at burnout is 3%.

c. The burn time cited here is for the assumption that the second stage it is closely similar to the second stage of the SS-11 as reported by astronautix.com at http://www.astronautix.com/u/ur-100.html. We are aware that the parameters provided by Astronautix may not be totally accurate and need further study. In addition, there are variants of the SS-11 upper stage that will also require additional studies to provide more accurate estimates of the properties of these systems. However, we believe that the general properties of the upper stage of the Hwasong-15 very closely fit the estimates used in our model. For example, our measurements of acceleration at launch indicate that the weight of the Hwasong-15 during the November 28, 2017 test was about 49,400 kg. The component weight estimates used in our rough model leads to a launch Gross weight of about 51,000 kg, assuming that there was a very minimal payload in the November 28 flight test. Additional analysis will be required for us to confirm these assumptions. But for now, we believe that our understanding of this system is sufficiently accurate to provide the policy community with useful information for its deliberations.

Figure 15



phase. The relatively long free flight phase leads to false impression that missile defense in the exoatmosphere could be relatively effective (in fact the flawed National Academy of Sciences report published in 2012 on ballistic missile defense incorrectly suggests that the relatively long flight time in a vacuum provides some kind of advantage for exoatmospheric missile defenses). This observation ignores fundamental fact that light and heavy objects will travel together in a vacuum creating a fundamental problem with decoys for any missile defense that must operate in the near vacuum of space.

ATMOSPHERIC REENTRY: THE CHALLENGE TO NUCLEAR WEAPON DESIGN

Although the development of the Hwasong-15 must be taken as a quite serious future nuclear-armed ICBM threat to the continental United States, it is also important to keep in mind that this threat also depends on the ability to build a nuclear weapon light enough to be carried by the Hwasong-15 and rugged enough to withstand the extremely high decelerations during atmospheric reentry.

Essentially nothing is known about the character of North Korean nuclear weapons except for the rough estimates of yields that have been derived from seismic measurements associated with underground nuclear tests.

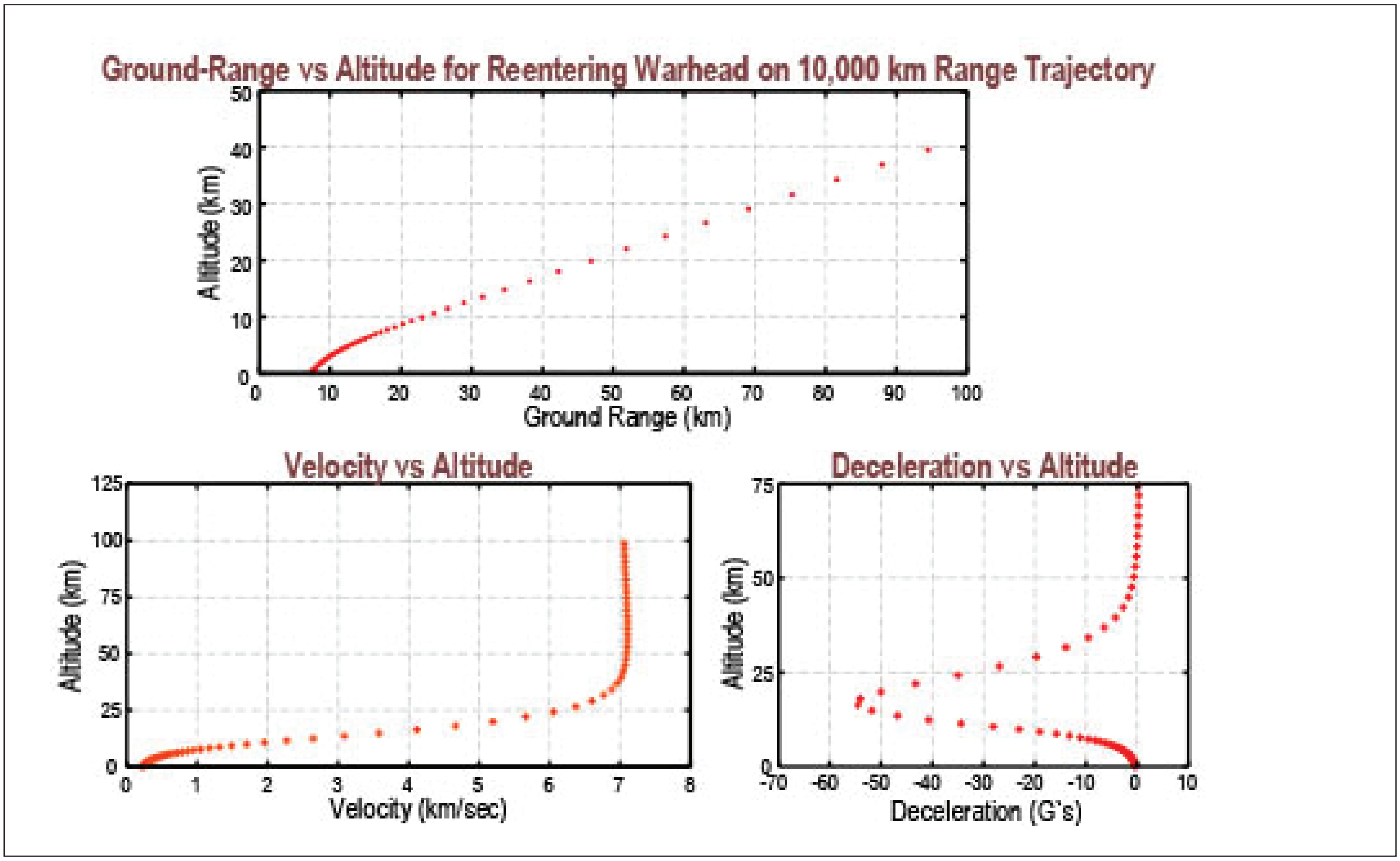
However, it is essentially universally accepted that all of the nuclear weapons designs associated with North Korean nuclear weapons require that a spherical shell of explosives be used to implode a spherical shell of uranium, plutonium, or a dual shell of uranium and plutonium. Even if North Korea has mastered multistage nuclear weapons, it will require an atomic "trigger" that uses a spherical implosive lens to ignite a secondary. A big design challenge for nuclear weapons that use spherical implosives is to construct the warhead so that its shape does not get distorted when it is subjected to very high deceleration forces. This problem has obviously been solved by the United States, Russia, and certain other states, but it is not known whether North Korea has made much progress in this aspect of nuclear design and it is certainly not known whether this problem has been solved for North Korea's higher yield and likely more massive nuclear weapons.

Figure 16 below shows three graphs that summarize the prodigious design challenges for nuclear weapons designers posed by atmospheric reentry decelerations on a 10,000 km range ballistic trajectory reentering the atmosphere on a minimum energy trajectory. The three graphs show the altitude versus range in one second intervals for a postulated arriving warhead with a ballistic coefficient of 500 PSF (PSF is pounds per square foot or 2,444 kilograms per square meter). As can be seen from an inspection of these graphs, a reentering warhead will experience a peak deceleration force of roughly 55G's if it arrives on a minimum energy trajectory (a local reentry angle of 22.55°). If the warhead is instead flown on a slightly lofted trajectory (reentering instead at a local reentry angle of about 27°), the deceleration forces will be about 65G's due to the more sudden encounter with the atmosphere caused by a steeper reentry trajectory. US ICBMs actually fly such slightly lofted trajectories in order to reduce the range errors at targets of ICBM range. If North Korea were forced to do something similar, the reentry forces would be appropriately higher.

The graph in Figure 17 on the next page shows the peak deceleration forces for atmospheric reentry of ballistic missiles flown to different ranges.

For example, a nuclear warhead carried to a 300 km

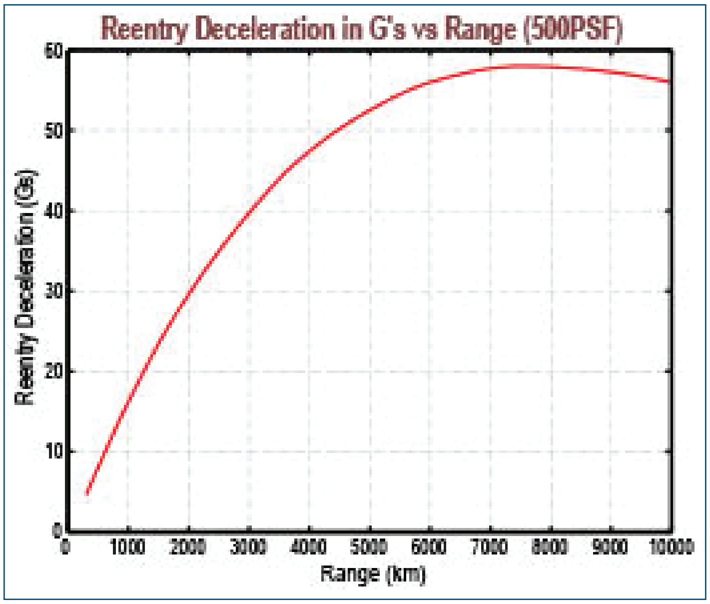
Figure 16



range by a ballistic missile will suffer a peak deceleration of roughly of 4.5 to 5 G's, at 500 km range it will suffer a peak deceleration of about 8G's, and at 1000 km Range a peak acceleration of about 16 G's.

For a range of roughly 3500 km from North Korea to Guam, the nuclear warhead would have to survive a deceleration in excess of roughly 40 G's, and to ranges above 5000 km the warhead would have to survive deceleration forces of above 50 to 60 G's.

Figure 17



These numbers indicate that the fact that North Korea has ballistic missiles that might carry enough weight to deliver a nuclear warhead to thousands of kilometers range does not immediately lead to the conclusion that these missiles now pose an immediate nuclear-armed ballistic missile threat to the continental United States, or Hawaii and Alaska. While this assessment could be comforting, it only means that the United States might have more time to address this threat than is generally assumed. It does not mean that such a threat will never appear.

A BALLISTIC MISSILE DEFENSE THAT COULD COUNTER NORTH KOREAN ICBMS

North Korea has demonstrated a new missile, the Hwasong-15, that could deliver relatively light and rugged first-generation nuclear warheads to ICBM range. It has also conducted successful underground tests of atomic or thermonuclear explosives with yields as high as roughly 100 or even 250 kilotons—comparable in yield to many current U.S. strategic warheads. Although there is no evidence at this time that North Korea has mastered the technology to ruggedize these warheads to survive the roughly 60 G deceleration and (to a much less extent) heating within reentry vehicles during atmospheric reentry at ICBM range, it is reasonable to expect that they could do so in time.

We sketch here an "Airborne Patrol System to Destroy North Korean ICBMs in Powered Flight" that would make it possible to destroy North Korean ICBMs with fast accelerating high speed interceptors before they could deploy very simple countermeasures that would defeat the current ground-based missile defense system. Although this concept is in principle simple, it requires the availability of extremely advanced space and aircraft based infrared sensors for early detection of ICBM launch and for providing critical tracking and homing information for the fast homing-interceptors. We emphasize that such a system is possible and only requires technologies that already exist and, in some important cases, are already deployed. However, the system requires that the technology be implemented correctly, or it will result in a defense that will be worthless.

Figure 18 below shows a diagram that lays out the system concept. The fast interceptors would be carried by drones that would patrol off the coast of North Korea. Some of the wavelength bands used by the space-based infrared early warning system (SBIRS) are in wavelength bands where water vapor has a very low absorption. Although light is still scattered by water droplets at these wavelengths, the very low electromagnetic absorption of water makes it possible to see-to-the-ground within these wavelength bands – even when there is a thick layer of clouds. When the rocket motor ignites, its plume interacts with the ground causing an extremely bright flash in the infrared that is characteristic of the missile, which allows for satellite identification and near instantaneous detection of the launch.

As shown in figure 19, It takes about 50 seconds for the Hwasong-15 to reach an altitude of about 12 km, where it would be above the clouds and highly visible at mid-infrared wavelengths. Because its plume is exceedingly bright, it can be seen from hundreds of kilometers range with small aperture telescopes that have the appropriate mid-infrared focal plane arrays.

This makes it possible to directly observe the rocket plume from drones and also from homing interceptors. At about the same altitude the ICBM would also be in line-of-sight of radars on ships at hundreds of kilometers range. Thus, the defense-system would have both timely and extremely reliable early detection of launch and high-quality tracking information very shortly after the launch of a North Korean ICBM.

In our assessment of this concept we assume that an interceptor can be launched from a drone roughly 50 seconds after the ICBM has been launched when it has reached an altitude of about 12 km (see Figure 19 on the next page).

Figure 18

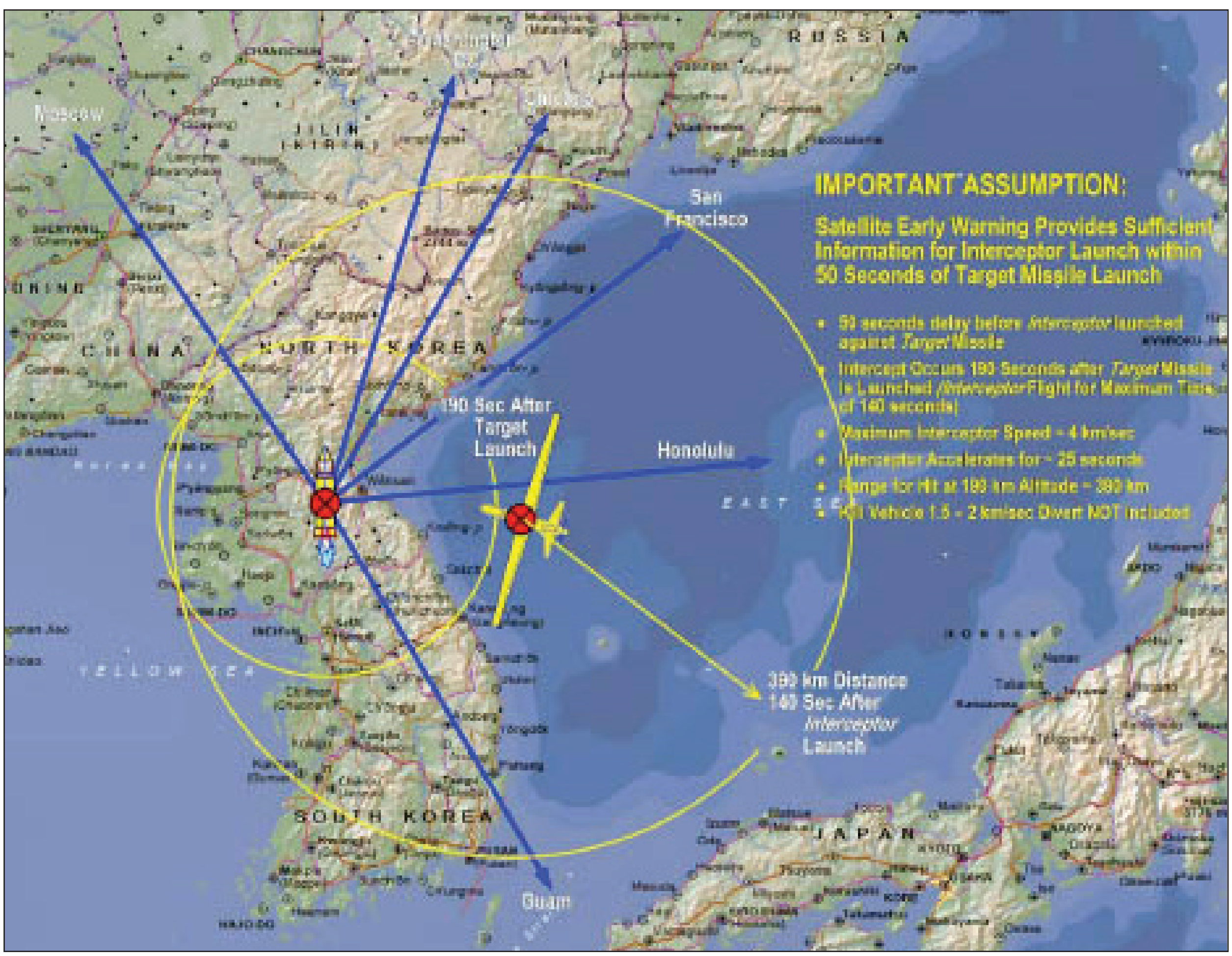
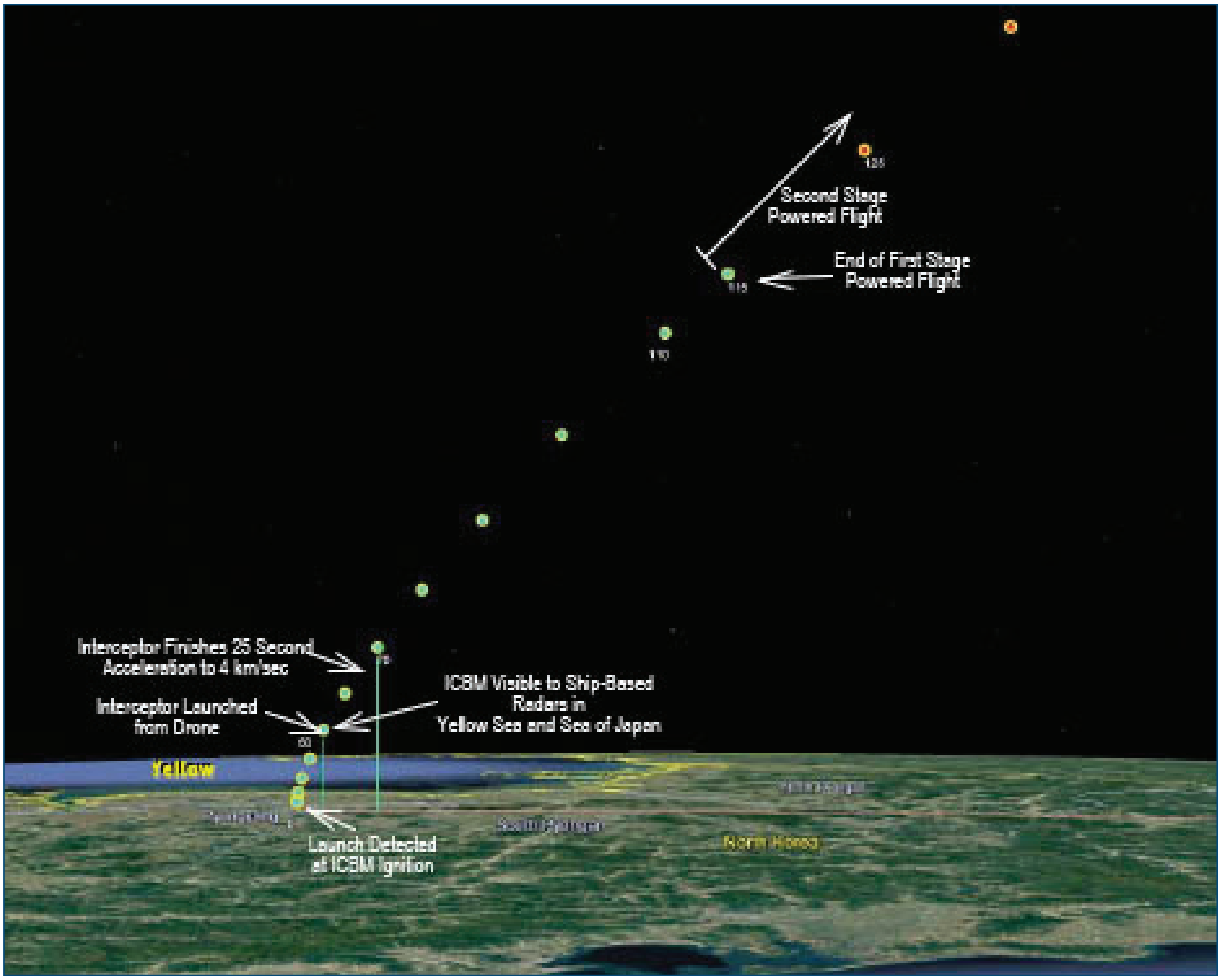


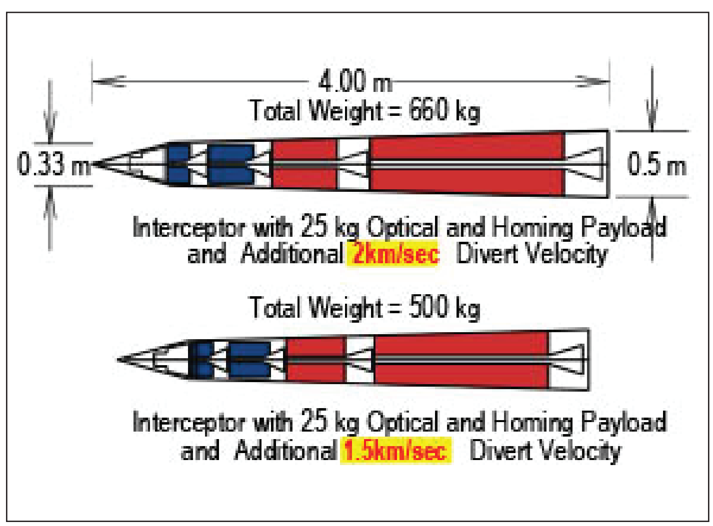
Figure 19



The two-stage anti-ICBM interceptor (shown in Figure 20) will be adequate for intercepting ICBMs launched from North Korea if it achieves a roughly 4 km/s burnout speed. The interceptor is intentionally designed to take about 25 seconds to accelerate to its final burnout speed. Higher burnout speeds are also possible, but this would increase the weight of the interceptor unless our technological assumptions are too conservative. The kill vehicle would home optically on the booster flame and the ICBM's hard body. The kill vehicle would weigh about 75 or 55 kg and would also be capable of an additional 2.0 or 1.5 km/s divert velocity so it can maneuver against and hit the unpredictably accelerating ICBM target. These weight numbers assume that the seeker and guidance control section of the kill vehicle weighs about 25 kg. The overall weight of this two-stage interceptor would be about 600 kg, although more detailed engineering analyses could produce interceptor weights that might be higher or lower.

The 25 second acceleration time allows for the interceptor trajectory to be updated as additional tracking information on the ICBM is obtained by the system. This highly accurate tracking system cannot determine an exact possible intercept point (PIP) because the details of the rocket's trajectory can change as it undergoes powered flight. In order to compensate for additional uncertainties in the PIP, the kill vehicle is itself constructed of two rocket stages which can impart an additional 2 km/s velocity change after the vehicle has been launched to 4 km/s. The second of the two stages in the kill vehicle is designed to impart a high level of acceleration (about 10 to 15 G's) for the last few seconds of the homing

Figure 20



process. This high end-game acceleration capability is critical for rapidly making final adjustments to hit the target. These velocity and high acceleration capabilities in the kill vehicle are absolutely essential for the successful implementation of intercepts.

Prior to the early work of Garwin and Postol (first circulated to the physics community in 1999), none of the boost-phase missile-defense concepts that were being promulgated recognized the need for a divert capability in the interceptor. This failure to recognize this absolutely essential basic requirement for intercept meant that all previous system concepts, including the space-based "brilliant pebbles," had no chance of working as claimed. This history of "technological exuberance" about varied missile-defense concepts should be carefully kept in mind when reviewing this and related system concepts that are supposed to destroy ICBMs in powered flight – or for that matter in the exoatmosphere.

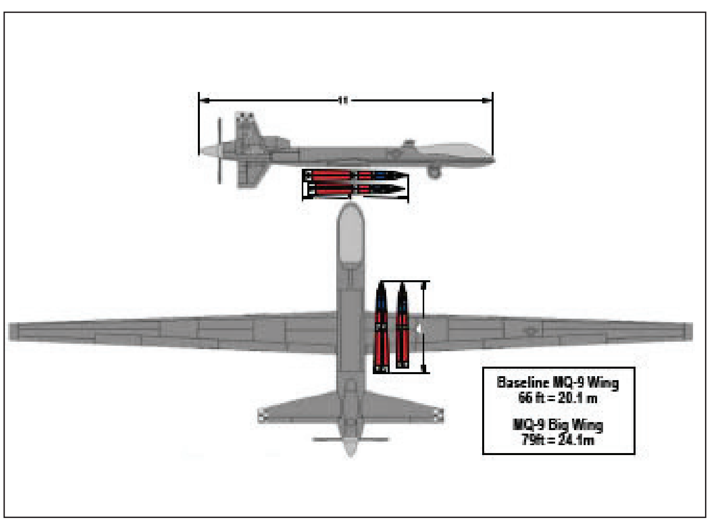
We currently believe that the well established Big Wing variant of the MQ-9 Reaper (Predator B) remotely piloted aircraft (RPA), shown in Figure 21 below, will be adequate for carrying the interceptors used in this defense-system.

The Big Wing MQ-9 has a loiter time of some 37 hours at 500 miles from its airbase in South Korea or Japan and could carry two Boost-Phase Intercept missiles assembled from available rocket motors, e.g., from Orbital ATK. It also has the advantage of being a relatively inexpensive drone costing tens of millions of dollars per vehicle rather than in excess of $100 million or more per vehicle.

All of the technologies needed to implement the proposed system are proven and no new technologies are needed to realize the system.

The baseline system could technically be deployed in 2020, and would be designed to handle up to 5 simultaneous ICBM launches, but a greater number of targets could easily be handled by simply expanding the number of interceptor-carrying drones.

Figure 21



The potential value of this system could be to quickly create an incentive for North Korea to take diplomatic negotiations seriously and to destroy North Korean ICBMs if they are launched at the continental United States.

The proposed Airborne Patrol System could be a "first-step system" that can be constantly improved over time. For example, we have analyzed the system assuming that interceptors have a top speed of 4 km/s with a 25 kg seeker. We believe that faster, or lighter and smaller interceptors can be built that would increase the firepower of the system.

Since the Airborne Patrol System would be based on the use of drones that would loiter outside of North Korean airspace, the electronic countermeasures needed to defeat distant surface-to-air missile defenses would be straightforward to implement because of the long-range between the drones and the air-defense radars.

The availability of relatively inexpensive high-payload long-endurance drones will also improve, along with the electronic countermeasures systems to protect them.

Figures 22, 23, and 24 can be used by those readers who are interested in understanding the details of the intercept process.

Figure 22 shows that if an intercept of the Hwasong-15 ICBM is to occur at about 250 seconds after initial rocket motor ignition, the kill vehicle will only have 200 seconds to fly to an altitude of about 400 km and to a down range distance of about 600 km from the ICBM launch point.

Figure 23 shows the range that can be achieved by both 4 kilometer per second and 5 km/s interceptors if they are to hit the ICBM at an altitude of about 400 km and after 200 seconds of flight. In the case of the 4 km/s interceptor, it can achieve a distance of a little over 420 km in the 200 seconds available for flight. The 5 km/s interceptor can achieve a range of 615 km/s. The reason for the very large difference

Figure 22

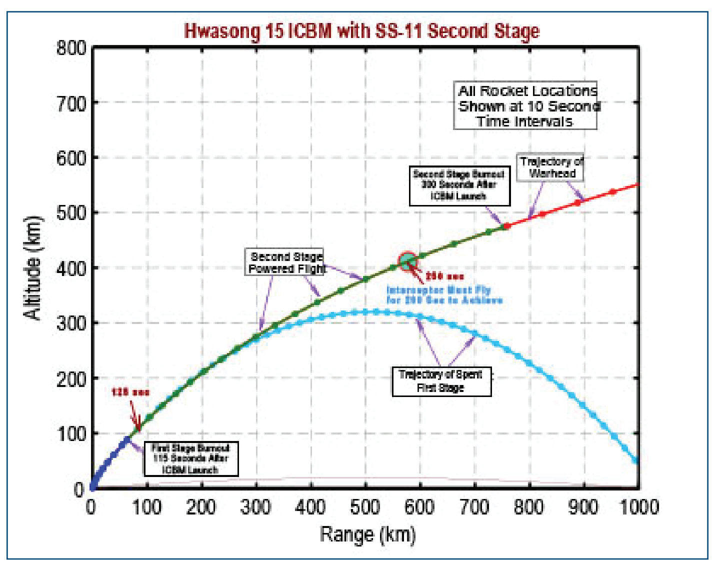
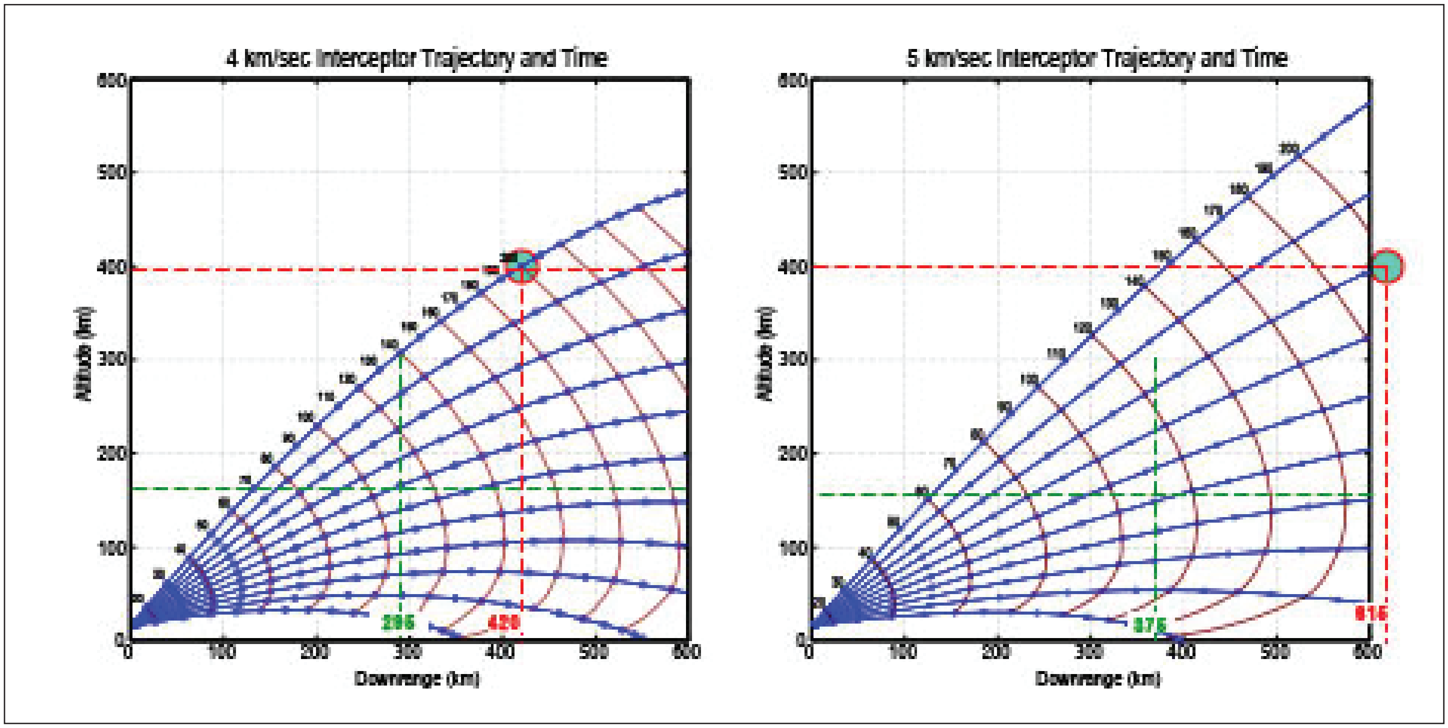


Figure 22 shows the time-of-flight range versus altitude for a Hwasong-15 ICBM launched at Washington DC

Figure 23



between a 4 kilometer per second and 5 km/s burnout is due to the 25 second acceleration time. This indicates that even a modest increase in the burnout speed of the interceptor can substantially increase kill ranges for the similar scenarios.

FINAL OBSERVATIONS ON THE MISSILE DEFENSE QUESTION

We have shown with clarity that a boost-phase missile defense system could be implemented by the United States against North Korean ICBMs that would require no technologies beyond those that have already been tested and used in other circumstances.

Yet this obvious insight about this ability to provide a robust and capable defense against a clearly emerging threat from North Korean ICBMs has yet to be grasped by those who have been given the direct responsibility for providing missile defenses for the nation

The drone-based laser system that is currently being proposed to the country by the Missile Defense Agency (MDA) requires technologies that are not already in hand. It will require lasers that have tremendously high-power densities, extreme precision pointing capabilities, and extremely low weights. Such lasers have not yet been built and it is entirely possible that these particular laser technologies may produce results for this task.

As for the Ground-Based Missile Defense System (GMD), any competent physical scientist knows that the infrared signal from a warhead in space can be readily altered or masked relative to other objects that have their own infrared emissions. In spite of this, the Ground-Based Missile Defense program was put forward into development in spite of the fact that it's two proof of concept experiments, the IFT-1A and IFT-2, completely failed to show that an infrared homing Kill vehicle could discriminate between simple balloon decoys and warheads.

Of even greater concern for the safekeeping of the nation, giant institutions like MIT Lincoln Laboratory, MIT itself, and the General Accounting Office, concealed these failures from the American people and the Congress. These institutions, and individuals within them, promulgated fraudulent science that claimed that infrared signals from these different space objects could be used to make it possible to discriminate between warheads and decoys. Now, 20 years after these individuals and institutions disserved the nation, we are now facing a potential eventual threat of nuclear-armed ICBM attack from North Korea.

It is remarkable that the Missile Defense Agency was created for the sole purpose of providing ballistic missile defense for the nation, yet it's only response to this threat has been to propose ballistic missile defenses that are not even based on sound science.

It is also a clear example of how great nations can fail when leaders become slaves to ideology and are also more concerned about their economic, political and bureaucratic interests than they are for the overall good of the nation.

Figure 24

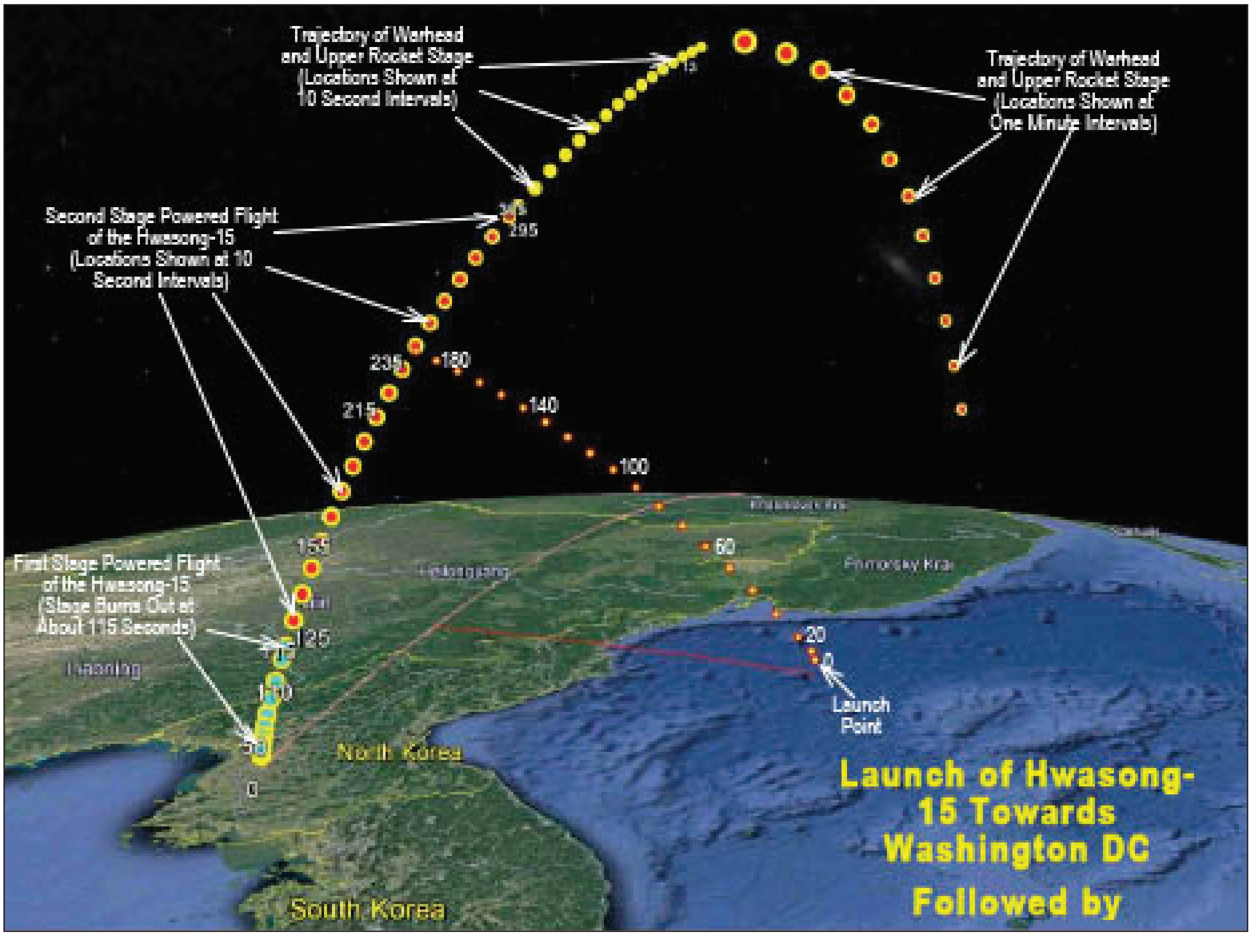


Figure 24 shows a three-dimensional depiction of an intercept of a Hwasong-15 at about 240 seconds after launch. In this case the interceptor has a burnout speed slightly higher than 4 km/s.

Comments on "The New Era of Nuclear Arsenal Vulnerability" by Lieber and Press

Frank von Hippel[1], 30 December 2017*

"*In the Cold War, we always thought that the danger was that the Soviet Union was going to conduct a surprise attack as a bolt out of the blue; and all of our policies, all of our weapons programs, and so on were based on responding to that. But that was never the threat. The threat was always that we would blunder into a nuclear war, and that threat was almost realized in the Cuban missile crisis*."

William Perry, former Secretary of Defense, *Arms Control Today*, December 2017, p. 43.

Lieber and Press' article is the latest in a long series that started in 2006 with "The end of MAD" in *International Security*, which was summarized in *Foreign* Affairs under the title, "The Rise of U.S. Nuclear Primacy". In that second article, the authors declared "Russia's leaders can no longer count on a survivable nuclear deterrent [and] China's nuclear arsenal is even more vulnerable to a U.S. attack."

This argument for the credibility of a bolt-out-of-the-blue U.S. nuclear first strike on non-alert Chinese or Russian nuclear forces, with millions of fatalities inevitably resulting, was shocking and resulted in a number of rebuttals – perhaps most thoroughly in an article by Bruce Blair and Yali Chen in *China Security*, a journal aimed at a Chinese as well as American audience.[1]

A decade later, in *Physics and Society*, Lieber and Press talk more cautiously about a trend toward vulnerability for Russia and China – perhaps because both countries are modernizing their nuclear forces and Russia is deploying a larger share of its ballistic missile submarines at sea and mobile land-based missiles in the field, making them less vulnerable.

In the jargon of nuclear-weapons policy analysts, what is being discussed are "counterforce" techniques for attacking an adversary's nuclear missiles and bombers before they can be launched. Arms controllers have for 50 years warned about the dangers of the U.S. military's pursuit of counterforce capabilities against Russian and Chinese nuclear weapons. George Rathjens wrote an excellent article on the subject in *Scientific American* in 1969, "The Dynamics of the Arms Race." When the Reagan Administration proposed adding 10,000 accurate counterforce warheads on U.S. ballistic and cruise missiles in the early 1980s, it caused so much alarm that a grass-roots movement to "freeze" the nuclear arms race rose in response and helped end the Cold War.[2]

Lieber and Press' efforts to publicize the vulnerability of Russia's and China's nuclear forces to a U.S. bolt-out-of-the-blue attack makes arms controllers nervous because such assertions feed the paranoia of worst-case analysts in those countries and increases the danger of accidental nuclear war.

In his book, *The Doomsday Machine*, Daniel Ellsberg recounts how, in the midst of the 1961 crisis over U.S. access to West Berlin, the Kennedy Administration communicated to the Soviet Union that new U.S. photographic satellites had discovered that the U.S. was way ahead of the Soviet Union in deploying intercontinental nuclear ballistic – an obvious counterforce threat.[3] This drove Khrushchev to the desperate stratagem of secretly sending medium and intermediate-range ballistic missiles to Cuba within range of the United States, triggering an extraordinarily serious nuclear crisis.

Counterforce drives a number of dangerous dynamics. One is that it is used to justify large nuclear forces. As we are learning again with North Korea, it would take only a few warheads to gravely wound a large nuclear-weapon state but many to target its nuclear missiles, the airports to which it might disperse its nuclear-armed bombers, its command centers and communications systems and its nuclear-weapon production and storage sites.

The demands for more warheads made in the name of counterforce during the Cold War led to even larger target lists. The U.S. nuclear target list for 1959 contained a total of 4609 Designated Ground Zeros (DGZs) for nuclear weapons including 178 in Moscow. Of the targets in Moscow, 3 were military and command headquarters, 8 related to radio and television transmission, 10 were military storage areas, 14 related to the electrical grid, 16 were aircraft body and engine factories, 18 related to liquid fuel storage and production, 33 were railroad yards and shops, and the remaining 90 ranged from factories producing agricultural equipment to antibiotics. There were similarly 145 DGZs for Leningrad, 68 in East Berlin, 39 in Warsaw and 18 in Beijing. In each of these cities, there was even one DGZ labeled simply "population".[4] In 1961, Ellsberg contrived to get the new Kennedy White House to ask the Strategic Air Command how many people its

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1 Bruce G. Blair and Chen Yali, "The Fallacy of Nuclear Primacy," *China Security,* Autumn 2006, pp. 51 – 77, https://www.issuelab.org/resources/436/436.pdf.

2 Matthew Evangelista, *Unarmed Forces: The Trans-national Movement to End the Cold War* (Cornell University Press, 1999).

3 Daniel Ellsberg, *The Doomsday Machine: Confessions of a Nuclear War Planner* (Bloomsbury Press, 2017) chapter 10.

4 "U.S. Cold War Nuclear Target Lists Declassified for First Time," https://nsarchive2.gwu.edu/nukevault/ebb538-Cold-War-Nuclear-Target-List-Declassified-First-Ever/. As of this writing, this was the only declassified target list.

Single Integrated Operations Plan would kill. To his surprise, they had an estimate, 600 million – or, as Ellsberg describes it, "100 Holocausts."[5]

A second perverse and dangerous consequence of nuclear counterforce is that it provides an incentive to launch on warning before the counterforce attack arrives. Although the commanders of U.S. strategic nuclear forces deny that this is a "hair-trigger posture," it is. The U.S. and Russian early warning systems have given false warnings of incoming attacks many times. Publicly-known cases on the U.S. side include a technician playing a training tape without informing the staff of the U.S. early-warning center and a faulty computer chip.[6] On the Soviet side, in 1983, the early-warning system misinterpreted the reflection of sunlight off the top of clouds as plumes from U.S. intercontinental missiles rising from their silos in the Great Plains[7] and, in 1995, a scientific rocket launched from an island off Norway was mistaken for a *Trident II* nuclear missile launched from a U.S. ballistic-missile submarine.[8]

Because the flight time of a ballistic missile from Russia to the U.S. is about 30 minutes and the flight time from the North Atlantic off Norway to Moscow is about 10 minutes, any decision on launch on warning must be made in a matter of minutes. Since we are still here, it appears that to date all false nuclear alarms have either been identified as such within this period or decisions were made to ignore them. But can we expect our luck to hold indefinitely?

5 *The Doomsday Machine*, Prologue.

6 *Recent False Alerts from the Nation's Missile Attack Warning System*, U.S. Senate Committee on Armed Services, 1980.

7 Colin Freeman, "How did one grumpy Russian halt Armageddon?" *The Telegraph*, 11 May 2015, http://www.telegraph.co.uk/film/the-man-who-saved-the-world/nuclear-war-true-story/ .

8 Geoffrey Forden, Pavel Podvig and Theodore Postol, "False alarm, nuclear danger," *IEEE Spectrum*, March 2000, pp. 31-39.

Thus, Lieber and Press have spot-lighted a serious concern for any U.S. adversary with nuclear weapons: the possibility that a U.S. President might opt for in a surprise attack to try to knock out its nuclear deterrent. At a time of worsening tensions with Russia, the idea that a bolt-out-of-the blue attack by the U.S. on Russia's nuclear forces is thinkable could make false alarms from Russia's inadequate early warning system more credible and increase the probability of Russia's hair trigger going off. China does not yet have an early warning system and has therefore not been in a position to adopt a launch-on-warning posture. But it is concerned about the possibility of a U.S. first strikes and this concern is being exacerbated by the U.S. drive to build a ballistic missile defense – nominally against North Korea. Perhaps in response, China has been building up the number of its missiles that can reach the United States, making the already difficult two-body problem of negotiating further reductions with Russia into a much more difficult three-body problem.

In the view of many arms-controllers, the United States and the world would be safer if we changed our policy to no first use, abandoned the options of launch on warning and nuclear preemption, and decided that no single person will have the unfettered power to launch U.S. nuclear weapons.

President Obama's failure to institute any of these changes demonstrates, however, that they will not happen in the absence of a powerful public movement. North Korea's increasingly credible nuclear threats and the Trump Administration's threats of preventative nuclear war may, for the first time since the 1980s, have created the conditions for such a movement.

In the past, American physicists have played an important role in educating their fellow citizens about the dangers from nuclear weapons and how those dangers might be reduced. I have written this in the hope that some members of the next generations of physicists will read it and carry on this noble tradition.

North Korean Nuclear Capabilities and U.S. Foreign Policy[1]

Mark S. Bell

Over the course of 2017, North Korea's nuclear program made giant leaps forward. While North Korea first tested nuclear weapons in 2006, the nuclear tests it conducted during its first decade as a nuclear power were unimpressive: its first four nuclear tests failed to achieve a yield larger than 15 kilotons, substantially smaller than the 25 kiloton yield the United States achieved in 1945 with the plutonium device dropped on Nagasaki. North Korea's achievements in 2017, however, should leave little doubt that North Korea is now a full member of the nuclear club. A nuclear test in September 2017 with a yield of around 150 kilotons demonstrated that North Korea has mastered the ability to produce sophisticated, high yield nuclear weapons (either a two-stage thermonuclear weapon or a boosted fission weapon). Its missile tests during 2017 were equally impressive, showcasing the ability to launch a genuinely intercontinental capability that could reach any major American city.

North Korea, in short, now has the capability to hold the cities of the United States (and its allies in Asia) at risk with powerful nuclear weapons. Policymakers in the United States must reckon with these capabilities and get used to the constraints they impose on U.S. foreign policy. As much as American policymakers might want to wish away North Korea's capabilities, or to play down North Korean capabilities, it is better to adjust the sails than to hope the wind disappears.

Today, North Korea benefits from nuclear weapons and this necessarily imposes constraints on U.S. foreign policy in the region. It is often said that nuclear weapons offer little beyond the ability to deter. In fact, precisely because they deter attack, nuclear weapons also act as a shield that reduces the risks and costs of pursuing a host of other foreign policy behaviors. Nuclear weapons can facilitate a range of objectives that states of all stripes may find attractive. Possessing nuclear weapons can allow states to act more independently of allies, engage in aggression, expand their position and influence, reinforce and strengthen alliances, or stand more firmly in defense of the status quo. States with nuclear weapons are aware of these benefits and use nuclear weapons to pursue them. This applies as much to democratic states committed to the status quo as it does to authoritarian or revisionist states.

Consider the case of Britain. A declining, status quo state when it acquired nuclear weapons in the 1950s, Britain was increasingly dependent on the United States for its security, facing growing challenges to its role as the preeminent power in the Middle East, while its commitments to allies were becoming increasingly uncredible. What did it do when it acquired nuclear weapons? Britain used nuclear commitments instead of conventional military commitments (which it could no longer afford) to reassure allies that were increasingly skeptical of Britain's ability to come to their aid. Similarly, Britain's nuclear weapons reduced the risks of acting more independently of the United States and of using military force to resist challenges to its position in the Middle East.

Or consider America's own experience with nuclear weapons. In the aftermath of World War II, a newly nuclear United States put in place a globe-spanning network of alliances and military bases and embraced a forward-leaning posture wholly at odds with its prior history of avoiding entangling alliances and staying out of European conflicts. In the words of Secretary of State Dean Acheson, this amounted to a "revolution" in U.S. foreign policy. And it occurred while the United States simultaneously demobilized its armed forces in the aftermath of World War II. Nuclear weapons allowed the United States to resolve the contradiction between expanding its commitments and reducing its ability to meet those commitments through conventional military means. With its nuclear arsenal, the United States could maintain (and take on) alliance commitments around the world without deploying the conventional military forces that would previously have been needed to make such commitments credible. Similarly, holding a nuclear monopoly allowed the United States to engage in more active and belligerent diplomacy in response to perceived Soviet aggression and misbehavior, despite the Soviet conventional military advantage in Europe. In the words of a 1948 National Security Council report: "[I]f Western Europe is to enjoy any feeling of security at the present time…it is in large degree because the atomic bomb, under American trusteeship, offers the present major counterbalance to the ever-present threat of the Soviet military power."

Today, North Korea is taking advantage of its nuclear weapons, just as past nuclear states have done. North Korea faces serious military threats from South Korea and the United States. South Korea is vastly more economically powerful and has the support of the most powerful state the world has ever known. Since the end of the Cold War, the United States —unconstrained by the absence of another superpower — has shown a repeated inclination to pursue regime change around the world, labelled North Korea as part of the "Axis of Evil," imposed punishing sanctions on North Korea, and kept tens of thousands of forces stationed in the region. What are the political priorities for countries that face these sorts of threats? States in this position would generally like to weaken their

1 This draws on "North Korea Benefits from Nuclear Weapons. Get Used to It," War on the Rocks, October 2, 2017, available at: https://warontherocks.com/2017/10/north-korea-benefits-from-nuclear-weapons-get-used-to-it/. For the research underpinning these arguments, see Mark S. Bell, "Beyond Emboldenment: How Acquiring Nuclear Weapons Can Affect Foreign Policy," International Security, vol. 40, no. 1 (Summer 2015): 87-119; Mark S. Bell, "Nuclear Opportunism: A Theory of How States Use Nuclear Weapons in International Politics," *Journal of Strategic Studies*, 2017.

adversaries' alliances, resist their coercion and encroachment, keep them as far from core territory as possible, retain the ability to threaten them, and be able to tolerate higher levels of escalation in crises. While states in a more benign environment face fewer constraints and so can pursue a wider range of goals, states facing serious threats must seek to improve their position against the threat. Nuclear weapons help them do so.

More specifically, North Korea would like to be able to stop the United States from flying military aircraft close to its territory (particularly the B-1B Lancer flights from Guam) and weaken the U.S.-South Korean alliance. It would like to show that Washington's threats of regime change or military intervention on the Korean peninsula are empty talk, and demonstrate that the United States is unable to shoot down its missiles. And North Korea may want to be able to more credibly threaten military action against South Korea. All of these make good strategic sense for North Korea as it seeks to reduce the threats it faces and strengthen its position on the Korean peninsula in the face of massive American and South Korean conventional military superiority.

How do North Korean nuclear weapons help it achieve these goals? By raising the dangers of escalation, North Korea seeks to drive wedges between the United States and South Korea and raise fears of alliance "decoupling," as well as to make it riskier for the United States to fly planes close to its airspace or engage militarily on the Korean peninsula. North Korea launches missiles, daring the United States to try (and quite likely fail) to shoot them down; it refuses to back down when challenged; and it raises the possibility of more provocative nuclear tests, such as an atmospheric nuclear test over the Pacific Ocean.

These actions are predictable, because they advance North Korean national interests. But they are also dangerous, raising the risk of escalation. This is a feature, not a bug, of North Korean strategy. Raising escalation risks is exactly how North Korea hopes to convince the United States to back off and, therefore, to improve its position on the Korean peninsula. And in the process of such escalation, North Korea might be entirely rational to use nuclear weapons first if things got bad enough: threatening the limited first use of nuclear weapons is a tried and tested strategy that allows states that are outmatched in conventional military power to deter stronger states. Pakistan uses this strategy today to deter Indian attacks, and the United States used it during the Cold War in its efforts to deter the Red Army from invading Western Europe. This risk is exacerbated by the particular way in which the United States fights conventional wars. Any U.S. military operation against North Korea would likely begin with attacks against North Korean Command and Control systems that would threaten North Korea's ability to use its nuclear weapons and raising the imperative for North Korea to "use them or lose them."

Any serious policy demands a dose of reality. Denuclearization and regime change are no longer achievable without risking tens (and potentially hundreds) of thousands of American lives. North Korea has nuclear weapons, benefits from having them, and has no interest in giving them up. Denying this reality is not only delusional, but in fact encourages North Korea to take more belligerent actions, accelerate its nuclear program further, demonstrate its capabilities more clearly, and further exacerbate the spiral of escalation.

A better approach would be to seek limited concessions from North Korea in exchange for limited concessions by the United States. For example, North Korea might agree to eschew missile tests over the territory of South Korea and Japan, if the United States limited flights of B1-B bombers close to North Korean territory. Such a deal would acknowledge that North Korea's capabilities impose constraints on U.S. foreign policy and grant North Korea benefits. At the same time, it reduces the risks of miscalculations or accidental escalation, diminishing North Korean fears of a surprise attack by the United States that could trigger incentives for North Korea to use nuclear weapons, and lending some stability to U.S.-North Korean relations. And if North Korea violated the deal, the U.S. could easily resume those flights.

North Korean nuclear weapons constrain the United States and its foreign policy in the region. But this does not mean the United States has to acquiesce to every North Korean provocation. Nuclear weapons might be useful, but they do not grant states free rein in international politics. During the Cold War, the United States accepted that it was not feasible to persuade the Soviet Union to give up its nuclear weapons, but this did not mean accepting every Soviet act that went against U.S. interests. Rather, it constrained what the United States could achieve because it had to recognize the reality of Soviet nuclear weapons and the benefits they provided to the Soviet Union. Today, denuclearization of the Korean peninsula is not a plausible goal, but the United States can nonetheless likely deter North Korea from taking the actions it worries most about, including an invasion of South Korea.

There are no free lunches in international politics. If the United States wants North Korea to constrain its nuclear program, it will need to offer North Korea something in exchange. And if the United States tries to pursue regime change or denuclearize North Korea by force, it must accept that North Korean nuclear capabilities allow it to force the United States to pay a high price for doing so.

Mark S. Bell is an Assistant Professor of Political Science at the University of Minnesota. His research focuses on nuclear weapons and proliferation, international relations theory, and U.S. and British foreign policy. His writings and research are available at www.markbell.org.

Why Undergraduates Can Improve Physics Through Policy

Riley Troyer, A physics undergraduate at the University of Alaska Fairbanks and a 2017 Mather Science Policy Intern

The AIP Mather Science Policy Internship, is a program funded by Dr. John Mather, the 2006 physics Nobel Laureate and current Senior Project Scientist for the James Webb Space Telescope. Each summer, two physics students are paid a stipend to work as interns for a congressional office in D.C. The Society of Physics Students (SPS) organizes the internship as part of its summer intern program. Over the summer, the Mather interns work fulltime on Capitol Hill and participate in a variety of activities alongside the other SPS interns. The office duties depend on the individual but can be anything from answering phone calls to helping organize hearings. The Mather internship is a great opportunity for students interested in science policy to learn more about the field and potentially jumpstart a career.

During the summer of 2017, I had the opportunity of a lifetime. I was accepted as a Mather intern and travelled to Washington D.C., all the way from Fairbanks, Alaska. Yes, I know, for many people working in Congress is closer to their version of hell, but for myself, it was something I had dreamed about. I am part of a group of undergraduates who are interested in both physics and politics. From my experience, this group is a lot larger than many people realize and it is growing. Unfortunately, there are very few opportunities and very little information for undergraduates interested in science policy. I want to help change that by showing, through my experience, how big of a difference we can have by getting involved with policymaking and why there should be more opportunities like the Mather internship.

First, let me tell you a bit about myself. I'm a pretty "standard" physics student, a white male who started working toward a college degree right after high school. I bet you've never heard that story before. To make it a little more interesting, I'm studying at the University of Alaska Fairbanks and was born and raised here, amid natural phenomena which first got me interested in physics. For example, the Aurora is a common occurrence, and we usually experience the point of homogeneous nucleation at least once a year. That's when at -40 (pick your temperature scale) water vapor can no longer exist in the atmosphere and spontaneously forms into ice fog.

A few years ago my reasons for studying physics started to change. I don't remember exactly how it happened, probably related to the 2016 election, but I realized that science policy was an actual profession. I was intrigued. Call me cliché, but I've always wanted to use physics to improve the world to the greatest extent possible. National policy seemed like something that could have a big impact. I also enjoyed explaining physics and working with other people. I started looking for opportunities. There were a few, but unfortunately, most were unpaid or for graduate students. The AIP Mather Science Policy Internship, which was through the Society of Physics Students summer internship program was really the only good option. I applied, and as you've probably guessed, I was selected for one of the two positions. After a long and intense process, I got a position working for the majority side of the Senate Committee on Energy and Natural Resources. This was exciting, as the Mather internship had never placed someone in either a majority committee or in the Senate.

If it's been awhile since your last government class, committees are the policy workhorses of Congress. They review nearly all the bills that are introduced in their area of expertise. While Senators form the committee, it is the staff that does most of the work. Everything from crafting legislation and marking up current bills, to organizing hearings (events where experts speak directly to the Senators about a specific topic). The Senate and House committees are separate, and each committee is split into the majority and minority sides. The other Mather Intern was working for the minority side of the House Committee on Science, Space, and Technology.

My experience working for the committee was nothing but great. The chair of the committee is Senator Lisa Murkowski, from Alaska. While I don't agree with all of her positions, I think she is very reasonable and makes decisions with her constituents in mind. This attitude transferred directly into the committee atmosphere and the entire staff was excellent to work with.

So, I had a position as an intern in Congress, but what exactly did I do, and did it matter that I was a physics major? The answer to the second question is a definite yes. As I worked on various tasks for the committee, I found my physics education invaluable. One of my first duties involved summarizing some current high-energy physics projects including DUNE (Deep Underground Neutrino Experiment). I had arrived in the committee office about the same time that the budget request from the Trump Administration had been released. Naturally, the staff was interested in what was contained in the request, in particular for the Department of Energy (DOE), which puts a significant amount of funding towards high-energy physics.

As the summer progressed, I continuously used the skills from my physics major. Energy storage was a subject that the committee staff wanted to know more about. Systems like pumped hydro, compressed air, thermal storage, and batteries. The staff didn't have time to research this themselves, but I had a technical background, so they gave me the job. I spent a large portion of the summer researching energy storage and explaining the technical ins and outs to a mainly non-scientific audience. In the end, I authored a 15 page report on the issue to help educate the committee staff members.

The report was my largest project, but I also helped with various side tasks. Number crunching in excel, collecting signatures, and staffing the front office, among other typical intern tasks. I'll admit, my physics skills didn't directly apply to many of these, however, I never once felt like I was in over my head. Working in the Senate certainly wasn't easy, but I found that the challenges and stresses of a physics degree had more than prepared me for this work. In fact, this is something I thought a lot about. I believe physics undergraduates interested in policy are perfect candidates for congressional staff positions. Unfortunately, it can be a challenging area to get into, in part because there are very few opportunities for us to explore it.

In the coming years, I would like to see more of the professional physics societies invest in undergraduate internships in policy. Spending a summer on Capitol Hill, I didn't see as many staffers with scientific backgrounds as I would have liked. I believe that physics students can offer a solution to this problem and improve science awareness in Congress. More internships would allow more students to get their foot in the door for potential careers. If I decide to pursue a career in policy I know that my internship will make getting a job much easier. Getting a job on Capitol Hill often hinges on connections, inside knowledge, and prior experience, all of which I gained from the summer.

I know that quite a few organizations offer science policy fellowships, but from what I can tell, these are exclusively for graduate or postgraduate students. There is certainly a place for fellowships, but I think undergraduates can make just as big of an impact. In regard to congressional staff positions, the earlier you start the better. In addition, the necessary skills don't extend past the skills of a typical physics undergraduate.

I was surprised this summer by how much power and influence staff members have over policy. Almost all of the Senators statements, questions, briefings, etc. were written and prepared by staff members, the people I was working with. In my opinion, more science policy internships will lead to more scientifically literate people working in Congress. Because of how much power staff members have, I believe that more physics backgrounds in Congress will lead to an increase in funding for the sciences.

Undergraduate physics students can make a huge difference in science policy. We have the skills and knowledge, we have the interest and drive, all that we need is a little help getting started.

I would also like to give an enormous thank you to Dr. John Mather. It was his generous donation that supports this internship and allowed me to have this amazing opportunity.

If you are interested in hearing more about my summer experience, I kept a weekly blog as part of the internship. You can find it here: https://www.spsnational.org/programs/internships/2017/riley-troyer

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Innovations in High School Science and Mathematics Classrooms

Mary Beth Dittrich

It's an exciting time to be a high school science or math teacher. The classroom that we knew growing up is slowing fading into the shadows. Taking notes on a boring lecture is being replaced with video lessons, interactive projects, and group inquiry and investigation. As I reflect on my 15 years of teaching math, I have never been so encouraged by the future.

I teach at Carondelet High School – an all-girls, Catholic high school about 40 miles east of San Francisco. In our over-50 year history we have seen a dramatic change in the role of women in society and the work place. Employers who once sought out women for primarily support roles are now actively hiring them for top positions. Carondelet is addressing these changes in our world with new courses and new ways to teach them.

Here are some of the innovative changes we have adopted in the past four years.

PHYSICS 9

Four years ago we instituted a "physics first" program for our ninth graders. Using the *Active Physics* text, we introduced our girls to a hands-on, investigative physics curriculum. It is an algebra-based program in which they study units on motion, electricity, waves, and light. Each unit begins with a discussion of "what do you see" and "what do you wonder" about a presented situation. These discussions are followed up with more classical physics experiments that combine continued observation and questioning with data collection and hypotheses. Only after completing these activities are they presented with the physical laws that govern what they have discovered.

In the beginning this approach was challenging. Our students were used to be spoon-fed the content. They had little experience in observing, questioning, wondering, and drawing their own conclusions. Many were frustrated with the experiments. They didn't know where they were going or how they were going to get there. "Just tell me the answer," was a common plea. Our teachers did not relent and as the year continued students grew accustomed to the process and learned the observation and reasoning skills that they would need in other courses.

Freshman physics is followed by chemistry in the sophomore year and biology junior year. Our life science teachers particularly favor this sequence of courses as it allows more time for the development of students' reasoning skills before studying biological systems.

One of the reasons we adopted this program was to have our students study science earlier in their high school careers and to encourage them to study more science. As a result 68% of our seniors have chosen to take a fourth science course (this is beyond the three-year graduation requirement). Several have even chosen to double up in their junior or senior year and will graduate with five years of science. Their course choices include AP-level Physics, Chemistry, Biology, Environmental Science, and Computer Principles, as well as Anatomy and Physiology, Marine Biology, Biotechnology, and Forensic Science.

FLIPPED MATHEMATICS CLASSROOM

The same year the science department instituted its changes, the math department decided to "flip" all of our Algebra 1 classes. The flipped classroom model takes what was traditionally done in class (lecture and direct instruction) and moves it to the home. Then what was traditionally considered homework (typically practice problems from the textbook) is now completed in the classroom. For their homework students watch and take notes on a teacher-produced video posted on YouTube. Students are then encouraged to communicate to their teacher their understanding of and any questions about the lesson. Currently we are using the EDpuzzle app to facilitate this conversation. When students arrive in class the next day, they are ready to engage with the material and to begin work on the traditional practice problems. The classroom environment becomes student-centered. The focus in class is on students practicing and producing work, not the teacher teaching the concepts in front of the class while the students listen. This model allows the teacher to monitor students more closely and to provide additional support to struggling students.

We strongly encourage our students to work in groups – to talk about the problems and their approaches to solving them. Our math classrooms are ringed with whiteboards. Students enjoy tackling challenging problems collaboratively at the board. It gets them up out of their desks working together. This also provides them the opportunity to see and comment on each other's work.

Our parents have wholeheartedly endorsed our approach. They are happy that they are no longer burdened by late night homework help and tears over confusing concepts. They appreciate the fact that their daughters are more responsible for and in control of their own math learning.

While this model has worked effectively for the past few years, it has had its limitations. All students still progress through the material at the same teacher-led pace. Some are anxious to move faster bored by a repeat of their eighth grade math course. While others needing a slower pace get left behind never completely mastering the concepts. As well, we felt the need to incorporate more practical application (word) problems that are the reason behind why we do math in the first place. This has led us to a total rethinking of our Algebra 1 program and eventually Geometry and Algebra 2.

REDESIGNED ALGEBRA 1 CURRICULUM

In the 2018-2019 school year we will be rolling out a completely redesigned Algebra 1 curriculum. We will remove remedial and honors distinctions from our existing courses and enroll all ninth grade students not taking Geometry into a self-paced, personalized mastery Algebra 1 program. Students will be working collaboratively in fluid groups as they self-pace through the curriculum. They will have the ability to spend more time on topics if needed or can advance at a faster pace potentially completing the Algebra curriculum in less than one year and continuing on to Geometry. Students will also be able to self-select and honors distinction.

The number of rote, out-of-context exercises will be limited. Students will complete just enough of these to show mastery. They will then move on to practical, cross-curricular application problems solved collaboratively in a group. The unit will culminate in a topic challenge (a multi-faceted application) and an assessment (test).

We have purposely removed the traditional textbook and language such as "chapters," "sections," and "problems." Currently very few students see a relationship between what they just did in the current chapter to what they will be doing in the next. Too often they learn the material for the test without seeing its connection to the whole of mathematics or to life outside of school. We want to provide them with challenging, deep and inter-connected math tasks that allow them to struggle, persevere, discover and grow.

As I said earlier, we will begin this program next school year. As such, we are still in the planning process. It is a daunting, yet exciting, task to completely reshape a mathematics program. A colleague in the English department recently asked me, "What if it doesn't work?" – to which I replied, "It will. We will make it work." That's exactly the attitude we want our students to have.

A NEW MINDSET

Underlying our curriculum changes, particularly in the math department, is the desire to create and nurture in our students a growth mindset. The concept of a growth mindset was put forth by Carol Dweck in her book *Mindset: The New Psychology of Success*, 2006 and applied to mathematics education by Jo Boaler in her book *Mathematical Mindsets*, 2016. A person with a growth mindset believes she can learn anything with enough hard work and perseverance. Her potential is limitless. She embraces challenge. She sees failure as an opportunity to grow and feedback as constructive.

Contrast this with a fixed mindset which says that we were born with certain talents and abilities. Our abilities are unchanging and our potential for growth is limited. Unfortunately this is the fixed mindset math education that most of our students received in their first eight years of schooling with its focus on rote memorization, speed, and problems solved in a vacuum. This system clearly defined who was good at math and who wasn't. Ability groups pigeon-holed students further reinforcing a fixed mindset which told them you will always struggle with math. Because of this, too many of our students, and unfortunately their parents as well, believe that they don't have a "math brain" and therefore will never be "good" at math. This is why our math department has embraced the growth mindset and share these insights with our students on a daily basis.

My colleagues in the math department and I love both mathematics and teaching. We want to convey this passion for math to our students. We want them to realize that anyone can master mathematics. We want them to see the importance of determination and grit. We want them to know that their brains can grow. We want them to take their time and think deeply about a problem. We want them to struggle to understand how and why something works the way it does – how it applies to different situations. We want our students to see that math is beautiful, creative, and surrounding them. It is patterns and shapes and colors. It is so much more than equations and solutions – so much more than they ever saw in school.

WHY?

I recently saw a sweatshirt that said, "Innovate or Die." While it momentarily took me off guard, I do believe it. The world has changed dramatically in the last 50 years – and it isn't going to stop changing. Neither should the way we teach our young people. A continual review and updating of our teaching practices is imperative. Our students need to be ready for a world and a job market that doesn't yet exist. They will need skills we can't even imagine. To be ready for this future our students need teachers today that are forward-thinking – teachers who embrace and welcome the changes ahead. They need teachers who are willing to try new methods, to take chances, to be passionate and bold. As I said above, it is an exciting time to be a high school science or math teacher.

Mary Beth Dittrich has been teaching math at her alma mater Carondelet High School in Concord, CA for the past 15 years. Previous to that she taught Religious Studies and served as the school's Dean of Students and Academic Advisor. She and her husband Tom, a physicist at Lawrence Livermore National Lab, live in Danville, CA.

REVIEWS

The author of the following review, Leonard Solon, died recently. He was a long-time contributor to these book review pages. He was 92.

Louis Harold Gray: A Founding Father of Radiobiology

Springer Biographies 2017, hardcover $89.99, ISBN 978-3-319-43396-7, e-book $69.99, ISBN 978-3-319-43397-4. By Sinclair Wynchank

This is an interesting and comprehensive biography of the pioneer radiobiologist Louis Harold Gray (1905-1965). Gray's name is incorporated in a fundamental dosimetry unit (i.e. one gray equals one joule of absorbed dose of ionizing radiation in a material). Gray's early studies were done at Trinity College, Cambridge, where he received a scholarship at the age of 18. He was at the top of his class and subsequently admitted to the Cavendish Laboratory at Cambridge University, one of the most important scientific institutions in the world. Its associates included Ernest Rutherford (1871-1935), whose experiments led to the understanding of the existence of the atomic nucleus; Joseph Thompson (1856-1940), discoverer of the electron; and James Chadwick (1891-1974), discoverer of the neutron and also Gray's PhD mentor. An important outcome of Gray's research at Cambridge was the Bragg-Gray Cavity Theory discovered independently by Gray and was one of the elements in the Nobel Prize awarded to William Henry Bragg (1862 - 1942) relating the absorbed dose in a material to the wall surrounding the cavity.

Gray's later work in hospitals, which was of greater personal interest to him, involved the application of radiation therapy in treating cancer patients. Gray's fundamental work in this area led to the conjecture that he might have achieved the Nobel Prize himself had he not died at a comparatively young age.

Wynchank informs us he spent several decades on Gray's biography, and worked exhaustively not only to address Gray's numerous scientific achievements but also to take us on a fascinating journey, joined by his colleagues and teachers of Gray's early life, in early 20th century England.

The book is an expansive view of Gray's personal character, his social contacts, his marriage, and his handling of scientific setbacks and controversies. Wynchank has great warmth and affection for his subject as manifested by his interviews with Gray's friends and family, and by the author's personal observations of face-to-face interviews and anecdotes. The biography depicts Gray as a dedicated man of science.

The biographer writes in a fashion that will be helpful to readers not acquainted with radiobiology and its ancillary subjects. One drawback is its lack of an index, which this reviewer and readers would have found useful. There is an appended list of several sources for the reader.

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Nuclear Weapons and Related Security Issues

Edited by Pierce Corden, Tony Fainberg, DavidHafemeister and Allison Macfarlane. American Institute of Physics Conference Proceedings #1898, 299 pp., 2017, ISBN 978-0-7354-1586-7, paperback.

Since the early 1980's the Forum on Physics and Society has sponsored short courses on nuclear weapons and the arms race. This volume comprises papers presented at the fifth and most recent such gathering, which was held 21-22 April 2017 at the Elliott School of International Affairs of The George Washington University. The course attracted some 120 attendees and was organized by the editors and co-sponsored by the Elliott School, the GWU Nuclear Science and Security Consortium, the American Association of Physics Teachers, and the Federation of American Scientists. Powerpoint files of the talks are at https://blogs.gwu.edu/nuclear-policy-talks, and the papers themselves are freeathttp://aip.scitation.org/toc/apc/1898/1?expanded=1898.

The proceedings of three of the first four of these short courses were reviewed in the April 1982, January 1989, and October 2014 editions of *P&S*. The gap in the 1990's reflected the optimism of the end of the Cold War and substantial reductions in the numbers of deployed American and Soviet/Russian nuclear weapons at the time. I had the pleasure of writing the October 2014 review, and remarked that I imagined "some years hence" another reviewer would be offering comments on a similar volume. My unanticipated prescience speaks to the deterioration in the world political and arms-control environments since then.

The 29 contributions are gathered under four topics: Strategic Nuclear Weapons, Multilateral Arms Control, Nuclear Nonproliferation, and Terrorism. The subjects are, however, broader than purely nuclear weapons, also touching on transportation security technologies, drones, and conventional, chemical, and biological weapons. Appendices include David Hafemeister's handy chronology of weapons of mass destruction (updated from the 2014 proceedings), brief biographies of authors, and a list of attendees. A useful addition would have been a glossary of the numerous acronyms.

About 40% of the contributions are exact or approximate reproductions of published articles and books. Examples include papers based on Joel Shurkin's recent biography of Richard Garwin; Harold Feiveson et. al's *Unmaking the Bomb* (reviewed in P&S April 2014); Frank von Hippel's study of Sakharov, Gorbachev, and nuclear reductions (*Physics Today* April 2017); Alex Wellerstein and Edward Geist's analysis of the development of the Soviet hydrogen bomb (*Physics Today* April 2017); and Siegfried Hecker's 1000-page, two volume work *Doomed to Cooperation* Russian-American inter-laboratory cooperation. It is certainly convenient to have these boundwith the new contributions in a single volume.

The following paragraphs summarize the take-away messages from some of the nuclear-oriented papers in each of the four sections of the proceedings.

Strategic Nuclear Weapons. These10 papers open with Steven Pifer's review of the history of deployed US-Russian nuclear weapons and arms control agreements, along with a sobering menu of various pressures facing these agreements: The Intermediate Nuclear Force (INF) treaty is in peril due to mutual accusations of violations and the acquisition of such weapons by China, India, Pakistan, Iran, Israel, North Korea and others. America and Russia do not seem eager to open negotiations for a successor to the New START treaty and its very successful system of verification measures. And ratification of the Comprehensive Test Ban Treaty remains in limbo. Pifer argues that such ratification would go a long way to locking in advantages in knowledge of weapons performance acquired by the US. Ultimately, a breakdown of the now 50-year-old system of nuclear arms control agreements could return us to a situation of no caps on numbers of weapons and types of delivery systems.

Two papers following Pifer's remind us of the ever-present dangers of nuclear weapons, their fantastic costs, and their associated strategic-balance factors: Hans Kristensen reports that USA, Russia, France, and Britain boast nearly 1,900 nuclear weapons on prompt alert (ready to launch in under 15 minutes), and Amy Woolf summarizes ongoing modernizations of weapons and delivery systems, efforts which the Congressional Budget Office estimates may cost over a trillion dollars over 30 years. To be sure, Russia and China have been pursuing their own modernizations since before the US commitment to do so, and it would be naive to imagine any party unilaterally abandoning such efforts even if others did so.

The possibility of game-changing technologies compounds threats of instability due to uncertainties in future nuclear postures. Mark Lewis's paper explores one such technology, hypersonic aircraft and missiles, which could render defense systems impotent. Alexander Glazer's contribution reminds us that even as modernizations of weapons and delivery technologies advance, the last 20 years have seen much progress in the area of stockpile verification procedures. A remaining challenge is verification of dismantlement operations, although advances in cryptographic and virtual-reality systems may be of help in addressing these concerns. In the end all verification measures will run up against the hard reality of nations' reluctance to allow inspectors access to sensitive design or operational information.

Multilateral Arms Control. This section opens with a review of the Comprehensive Nuclear Test-Ban Treaty by Raymond Jeanloz. The US Senate rejected ratification of the treaty in 1999 over concerns that nuclear detonations could go undetected, but since then the International Monitoring System that supports the treaty has grown much more sophisticated and boasts a high probability of detecting even underground explosions "decoupled" from the surrounding earth. At the same time, experimental and numerical-simulation work in support of the Stockpile Stewardship Program have led to much improved understanding of weapons performance and aging issues. Two National Academy of Sciences reports have concluded the US can maintain a safe, secure, and reliable stockpile without returning to testing. There are now no credible technical arguments against ratifying the treaty. A companion paper by Edward Ifft describes the extensive onsite capabilities that the Comprehensive Test-Ban Treaty Organization has ready to deploy in the event that inspections are demanded. However, the treaty must be brought into force before these can be activated.

A contribution by Matthias Auer and Mark Prior describes the technicalities of the CTBT sensor network, but this is reproduced from a 2014 article and comes off as dated because its opening passage refers to speculation on a possible fourth North Korean Nuclear test (there have now been six). A paper by Reis et. al. describes the Stockpile Stewardship Program. While this too is reproduced from an earlier publication (2016), one statistic did catch my attention: At the height of the Cold War, the US exploded, on average, one nuclear device per week at the Nevada Test Site. An original contribution by Rachel Stohl describes the approximately $80-billion *conventional* arms industry, a significant cause of human misery that is easy to overlook in view of all of the attention devoted to nuclear weapons. Papers by Theresa Hitchens and George Lewis on space weapons technology and the effectiveness of ballistic missile defense will be of interest to readers concerned with the militarization of space and the difficulties of missile interception presented by technical limitations of sensors in kill vehicles. This section closes with a paper on treaties governing chemical and biological weapons and the United Nations Security Council's inaction in holding Syria accountable for using chemical weapons.

Nuclear Non-Proliferation. This section opens with a lengthy paper by George Perkovich on the July 2015 "Joint Comprehensive Plan of Action" that was negotiated to address Iran's nuclear program. Despite President Donald Trump's criticism of this agreement, knowledgeable observers credit it with greatly reducing the prospect of a regional nuclear arms race over the next 15 years. Apropos, the next paper, by Daryl Kimball, addresses the status of the 1968 Nuclear Non-Proliferation Treaty in his article "the Age of Trump." Current stresses on the non-proliferation regime include diplomatic rifts caused by the Russian invasion of Ukraine; alleged Russian violations of the Intermediate Nuclear Force treaty; expansion of nuclear weapons programs in India, Pakistan, and North Korea; and Trump's contradictory statements on disarmament and expansion of American nuclear capabilities.

Other papers include a review of IAEA safeguard systems, an analysis of an internationally unique Brazil/Argentina safeguard agreement, proliferation risks presented by products of the nuclear power infrastructure (dual-use technologies, waste, enrichment and reprocessing facilities), and a contribution by conference organizers Corden and Hafemeister on nuclear proliferation and testing. While this is reproduced from a *Physics Today* article (April 2014), its core message is still relevant: The reason the US and other nuclear-weapon-possessing states don't test nuclear weapons is that to do so would not only invite a new arms race but would make addressing nuclear programs in countries such as North Korea much more difficult.

Terrorism. The prospect of nuclear terrorism is the ultimate low-probability, high-consequence scenario. Papers in this section examine different aspects of this situation.The first contribution, by Miles Pomper and Gabrielle Tarini, surveys the general landscape of nuclear terrorism, identifying three general types of scenarios. These progress from easiest to hardest (for the terrorists), with corresponding escalation of damage and casualties: a radiological device (dirty bomb), an attack on or sabotage of a nuclear facility (reactor or waste repository) to either acquire nuclear material or disperse it over a wide area, and detonating a nuclear explosive. The second of these scenarios is perhaps the most alarming, as an attack need not be by direct action: Standoff attack scenarios involving rockets, mortars, drones, or cyber-infiltration need to be considered in the security plans of potential target facilities. Also, consideration of potential adversaries cannot be restricted to jihadist-type groups: Far-right militants have also expressed interest in nuclear terrorism.

Anthony Fainberg's lengthy paper on technical and policy approaches to countering terrorist threats serves as an excellent primer on the history of terrorism, the evolution of terrorist targets and weapons, and possible countermeasures that can be deployed to prevent and contain such incidents. A brief paper by longtime FPS participant Peter Zimmerman analyzes attempts to calculate the probability of terrorists successfully developing a nuclear weapon. He points out that, despite their apparent sophistication, such efforts are futile because such an event would be so unique that normal statistical techniques simply do not apply. Rather, he posits that we need to analyze the steps involved in such a program and how they could be detected and thwarted. The final paper, by Hugh Gusterson, examines the history, tactics, operational protocols, and legality of, drone warfare. It emphasises the vexing question of civilian casualties.

Overall, these papers provide much food for thought–much of it depressing–for scientists and policymakers interested in the myriad issues addressed. The spectrum of state-based and non-state-based nuclear and other WMD threats is vast, but so too is the available suite of policy/enforcement and technical means of deterring such threats. The fate of Western civilization may depend on whether we have the will and imagination to use them wisely. And yes, I confidently predict that not too many years hence another reviewer will be offering comments on a similar volume!

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