Hypersonic Technology: An Evolution in Nuclear Weapons?

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Abstract

Hypersonic delivery systems are a grave concern because they are potentially fast and maneuverable enough to evade existing defensive systems. As the US military considers upgrading its nuclear arsenal, hypersonic delivery systems are one possible option. Increased research on hypersonic technologies over the past two decades demonstrates there is technical feasibility for hypersonic conventional weapons. The case for nuclear-armed hypersonic weapons (NAHW) is more complicated. This article considers NAHWs from the point of view of deterrence thinking and suggests a NAHW is consistent with current US thinking about deterrence with respect to existing ballistic missiles, cruise missiles, and missile defense systems. However, we conclude that there are few advantages to hypersonic nuclear delivery systems relative to existing nuclear weapon delivery systems.*

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The Department of Defense under secretary for research and engineering, Michael Griffin, recently declared hypersonic technology to be his top technology priority.[1] The former commander of US Strategic Command, Gen John Hyten, says the US currently does not have "any defense that could deny the employment" of hypersonic weapons.[2] These statements demonstrate how hypersonic weapons present unique strategic opportunities and challenges. For example, hypersonic weapons promise to defeat existing missile defense systems—something limited salvos of intercontinental ballistic missiles (ICBM) may be unable to do.[3] Currently, the US, Russia, and China are actively working to develop advanced hypersonic weapon systems, and other countries are interested as well.[4] Public reports describe US hypersonic development in

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terms of conventional systems capable of providing a prompt, long-range strike capability.[5]

There has been significant discussion of conventional hypersonic weapons. Much of this research considers whether conventionally armed hypersonic weapons might prove destabilizing.[6] However, there has been little specific examination of whether hypersonic delivery systems for nuclear weapons may prove destabilizing. We argue that US nuclear-armed hypersonic weapons (NAHW) will not be destabilizing in terms of nuclear deterrence.

The analysis starts by considering how evolutionary technological changes developed concurrently with deterrence thinking and how previous scholars evaluated technology's impact on deterrence thinking. Then it assesses how a NAHW might affect deterrence thinking. We compare future NAHWs against three existing nuclear-related technological systems: ICBMs, cruise missiles, and missile defense. The analysis examines the historical development of each element to show that US hypersonic technology is evolutionary relative to these elements. It also considers whether the elements will combine synergistically. Next, our analysis appraises the potential implications of two sides having NAHWs, again in the context of the key parameters of existing systems. Ultimately, we conclude that hypersonic development is evolutionary; therefore, NAHWs will not be destabilizing relative to existing nuclear weapons delivery technology or offer great advantage. While a historical analysis of hypersonic component technology shows rapid advancement, no NAHW has been openly fielded.

Evolutions and Technology

Hypersonic vehicles, commonly characterized as highly maneuverable systems traveling at speeds of at least Mach 5, comprise two classes of hypersonic systems: hypersonic cruise missiles and hypersonic boost glide vehicles.[7] The word *hypersonic* generally refers to these two systems. ICBMs and submarine-launched ballistic missiles (SLBM) travel faster than Mach 5 but are not maneuverable, so they are not considered hypersonic weapons for purposes of this article. Here the focus is on the implications of high-speed, maneuverable nuclear weapon systems. Maneuverability allows NAHWs to potentially evade missile defense systems. This makes them potentially useful against adversaries with effective defenses against ICBMs, SLBMs, or nuclear-armed cruise missiles.

Hypersonics is not actually a single technology. Rather, it is a class of related technologies that must be combined together to form an operationally useful system. The Defense Advanced Research Projects Agency (DARPA) reports that successful hypersonic systems require the effective combination of a number of technologies, including high-speed supersonic combustion ramjet (scramjet) engines, high-temperature materials capable of managing the high heat loads associated with hypersonic flights, advanced manufacturing techniques, and advanced vehicle configurations.[8] An analysis of the journal publications in each area, shown in figure 1,[9] demonstrates that hypersonic technologies have been changing rapidly over the last few decades.[10]

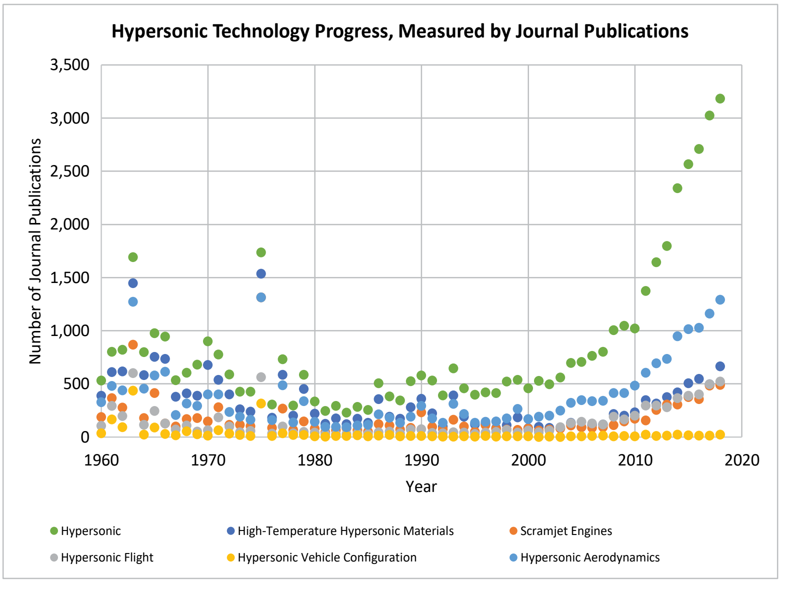

Figure 1. Number of journals published yearly reporting progress in hypersonic and hypersonic component technology

The rapid changes to hypersonic technologies do not necessarily lead to radical alterations in our thinking about deterrence. Many technological changes are evolutionary improvements in technology that only catalyze evolutions in strategic thinking. However, in the case of nuclear weapons, the capability improvement was so radical that the new technology revolutionized how nations thought about war. When a new technology like hypersonic delivery systems is developed, how should it be evaluated in terms of deterrence thinking? Will it turn out to be a breakthrough that significantly changes deterrence, or will it rather be an important but incremental change in existing technology?

Bernard Brodie proposed nuclear deterrence in 1946 in response to the tremendous power of nuclear weapons. To him, nuclear bombs represented a 700-fold increase of the destructive power provided by bombers, enabling a single aircraft on a single mission to potentially destroy a city.[11] While B-29s were vulnerable to various defenses—including fighter aircraft, antiaircraft weapons, or even preemptive ground attacks—the potential for destruction represented by nuclear-armed bombers was so great that Brodie argued the main purpose of nuclear weapons was prevention, not fighting.[12]

This concept was a revolutionary development in the thinking about war. Large armies had been used for centuries both to prevent attacks and to carry them out. As Thomas Schelling explained, prior to the advent of nuclear weapons, only the loser was punished—and then, only after it lost.[13] Nuclear weapons could destroy so much and so quickly, he argued, that annihilation could come to either side at any time during the conflict. Brodie and Glenn Snyder reasoned that nuclear weapons fundamentally changed warfare, making the case that the only purpose of nuclear weapons was to deter.[14] Schelling further expanded the ideas of deterrence, indicating that although nuclear bombs were not exploded during conflicts such as the Korean War, the Cuban missile crisis, and the Vietnam War, the specter of nuclear weapons loomed large in the minds of great powers—deterring escalation to even greater levels of conflict.[15] Writing in 1996, Robert Pape considered the role of bombing campaigns in war and suggested that nuclear bombs were far better suited to threats than to actual attacks. [16] In many ways, the theme of deterrence remained remarkably consistent over time.

While scholars wrestled with deterrence, nuclear weapons technology morphed to create new and improved bombs, delivery systems, and defenses. Great powers went from mere nuclear bombs to thermonuclear bombs; weapon yields increased from tens of kilotons to tens of megatons, tripling or quadrupling the size of a city that could be obliterated.[17] Bombers leveraged a combination of novel guidance technologies and new configurable wing-design technology. This flexibility allowed them to switch between fuel-efficient, high-altitude flights over friendly territory and less risky, low-altitude flights over enemy territory—greatly increasing aircraft range and survivability.[18]

Ballistic missile technology stemming from World War II was adapted to the US nuclear arsenal. US ICBMs were operational in 1958, and the first sea-launched ballistic missiles were deployed in 1960.[19] A whole host of technologies went into improving the range and accuracy of ICBMs, including high-precision inertial components, transistors for miniaturized navigation computers, smart fuses to handle missile navigation errors, and rapid retargeting technologies to reduce the number of missiles needed to attack targets.[20] Air-launched, nuclear-armed cruise missiles were operationally deployed in 1958 with a warhead about 10 times as powerful as the weapon used in Hiroshima.[21] Air-launched cruise missiles supported standoff attacks by bombers and small engine technology increased effective missile ranges.[22] New materials allowed higher engine operating temperatures, in turn increasing fuel efficiency and range.[23]

Defenses against nuclear weapons advanced as well. Soviet developments in radar, command and control, and fighter technology further threatened bombers, driving requirements for missiles with improved standoff attack range.[24] More accurate ICBMs potentially threatened the survivability of adversary ICBM forces.[25] The survivability of ICBMs was increased by developing systems and technology for hardening, redundancy, multiple warheads, concealment, and mobility.[26] Increasingly accurate delivery systems developed to thwart hardening and concealment are increasingly being offset by increased intelligence, surveillance, and reconnaissance (ISR) capabilities.[27] In-flight missile survivability improved through technologies such as decoys, chaff, alternate trajectories, radiation hardening, and electronic countermeasures.[28] In the 1980s, the US explored a host of new defenses against ballistic missiles under the aegis of the Strategic Defense Initiative.[29] Even after decades of unparalleled technological changes, the US nuclear arsenal remains postured in a way familiar to Brodie, Snyder, Schelling, and others. If defenses against and counters to hypersonic weapons eventually emerge, hypersonic weapons may not appreciably change strategic nuclear postures.

Writing in 1957, Kissinger evaluated the impact of coupling nuclear warheads to missile delivery systems, a relatively new technology at the time. His arguments can be grouped into two criteria.[30] First, technology should be evaluated relative to the advantages provided to one side, particularly in terms of existing systems. Second, eventually technological parity would be reached, and thus technology should be evaluated regarding the implications of both sides possessing the technology.

Using these benchmarks, Kissinger was skeptical about the utility of upgrading the missile-based delivery systems of the 1950s. Using the first criterion, he argued that once a missile was capable of traveling 5,000 miles in half an hour, additional increases in speed would "prove only marginally significant."[31] He added, "After a certain point, superiority in destructive power no longer pays strategic returns."[32] Kissinger reasoned that thermonuclear warheads were more advantageous to the Soviets than to the US because at the time, the US possessed a larger nuclear force.[33] Kissinger further noted that Soviet ballistic missiles were not a breakthrough because short-range missiles provided minimal advantage relative to the existing Soviet bomber force.[34] Each argument compared the capabilities of new and improved weapons to existing weapons and concluded that the small increases in capability were evolutionary.

Using the second criterion, Kissinger evaluated the implications of both sides having upgraded weapons. He reasoned that survivability through concealment, mobility, or dispersion made a successful first strike impractical for both sides.[35] Kissinger acknowledged that technical parity did not always equal strategic parity, arguing that SLBMs were more threatening to a naval power than to a landlocked nation.[36] This second criterion complements the first by considering technological developments relative to the overall strategic situation rather than simply in a vacuum. Considerations such as relative force sizes and force postures influence whether a technology has evolutionary or revolutionary implications for deterrence thinking.

Kissinger also considered future technology developments when ascertaining the implications of current technological developments. He stated that as one side builds missiles, the other side would reach parity relatively quickly.[37] Technology levels, he reasoned, are not inherently stable. In his mind, there is no such thing as equilibrium in terms of technology-based capabilities because parity is a fleeting thing.[38] Colin Gray used similar arguments to conclude that arms races are rarely destabilizing because as one side gains a technological advantage, the other develops a countermeasure. While supportive of pursuing technological changes, Gray remained unconvinced that new technologies would fundamentally alter the principles of deterrence because each technological advance would eventually be countered.[39]

These contentions acknowledge that major changes in military technology like the development of nuclear weapons altered the way nations viewed weapons and warfare. However, subsequent changes in weapons and weapon delivery technology have been evolutionary and have not significantly changed thinking about nuclear deterrence. While each side pursued technological developments to gain some advantages, historical analysis shows that when changes were evolutionary, the resulting instability was temporary. This brief overview of nuclear weapon delivery technology shows that scientific developments have been an ongoing evolutionary process. Most of the aforementioned improvements were adaptions of existing technologies. Despite all these technology changes, the basic form of the nuclear triad for deterrence is still largely recognizable even well over a half-century later. In 2018, the United States *Nuclear Posture Review* declared that the US continues to use a combination of nuclear-armed bombers, SBLMs, and ICBMs to deter nuclear attack, stating that US adversaries must understand that "any nuclear escalation will fail to achieve their objectives."[40]

This analysis clearly shows that most hypersonic component technologies are developing at an expeditious rate, especially compared to historical trends. However, while hypersonic technology is improving, technology improvements cannot be considered in a vacuum. Instead, determining whether hypersonic delivery technology is evolutionary or revolutionary requires a comparison with existing nuclear weapon delivery technologies. Reference points, such as the performance of cruise missiles or ICBMs, are needed against which to benchmark the progress of hypersonic technology.

Comparing Existing Nuclear Systems and Nuclear-Armed Hypersonic Weapons

One way to benchmark the impact of a potential future system is by analogy to existing systems. Many existing systems have a long history and have been thoroughly analyzed in terms of their impact on deterrence thinking. Second, any new system is going to potentially complement or replace existing systems, making them an appropriate baseline. ICBMs, cruise missiles, and missile defense are three analogs that have been analyzed regarding their impact on deterrence postures and thinking. Each component shares some similarities with a NAHW. A superposition of these three component features describes all the essential elements of NAHWs and provides key parameters that can be analyzed to determine if hypersonic technology is revolutionary or evolutionary for each component.

A *ballistic missile*, defined as "a projectile that assumes a free-falling trajectory after an internally guided ascent," travels very fast—a characteristic of all forms of hypersonic technology.[41] Thus, ICBMs are a good analog to future long-range NAHWs. There is keen interest in increasing the range of hypersonic weapons, suggesting that the long range of ballistic missiles is another reason to include them in the model.[42] However, ballistic missiles are inaccurate and generally follow predictable flight paths, indicating that additional elements are needed for a working model useful for analyzing the range of future capabilities promised by NAHWs.

A *cruise missile* is defined in part by the Intermediate-Range Nuclear Forces (INF) Treaty of 1987 as "an unmanned self-propelled guided vehicle that sustains flight through aerodynamic lift for most of its flight path."[43] Cruise missiles are maneuverable, meaning they can make course adjustments to improve their accuracy or to avoid obstacles and defenses.[44]

The maneuverability of cruise missiles makes it difficult for defenders to determine their destination, potentially reducing the reaction time of missile defense systems. On the other hand, cruise missiles are relatively slow, making their maneuvers easy to track and leaving substantial time for defenders to react.

Missile defense systems are extremely complicated.[45] Just as there are many types of missiles each with its own combination of vulnerabilities and defenses, there are multiple types of missile defense systems, each a complex collaboration of sensors and shooters. Coordinating between the various elements presents huge technical challenges, especially for targets defended by layers of missile defense systems. Coordination between the various layers means missile defenses need enough time to operate effectively—a luxury that hypersonic weapons may not allow.

From a mathematical point of view, NAHWs can be seen as a superposition of three elements: ICBMs, cruise missiles, and the negative (opposite) of missile defense systems. The stability implications of NAHWs should be considered relative to changes in these three elements. The central features of NAHWs (speed, range, accuracy, and missile defense) are evaluated by considering whether hypersonic systems are a revolution or an evolution in the key technology associated with each element. The first three factors are evaluated quantitatively while the evolution of missile defense is evaluated qualitatively. The analysis concludes by considering whether the individual elements might combine synergistically to create a new path to a revolutionary technology combination.

Intercontinental Ballistic Missiles

ICBMs, the first component analog of hypersonic technology, will be analyzed in terms of changes to speed, range, and accuracy. It is important to consider ICBMs in the context of the other legs of the nuclear triad, so the development of SLBMs is considered here as well. The bomber leg of the nuclear triad is considered later in this section in terms of the technological evolution of cruise missiles. Gravity weapons employed as part of the nuclear triad are not considered in this analysis because gravity bombs have less in common with potential NAHWs than with existing missiles.

Figure 2 plots the speed of US ICBMs and SLBMs as a function of the year various systems obtained an initial operating capability (IOC). The system IOC is used because it provides a useful historical marker noting when a technology transitions to operational employment. Other measures of technological progress are possible, such as dates and results of key missile test flights. However, there is often considerable additional development necessary to go from a proof-of-concept test system to an operationally fielded system. For example, operational systems represent optimization between multiple contradictory requirements. Unlike prototypes, operational systems have additional requirements, such as terms of initial and recurring costs, usability, manufacturability, and sustainability in real-world environments. Furthermore, operationally deployed systems may have a different impact on deterrence than test systems that may fail to be operationally deployed.

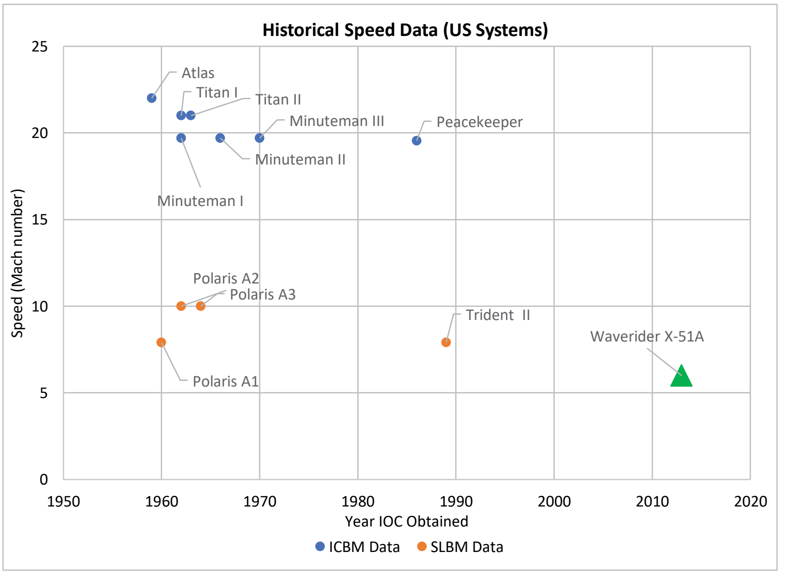

Figure 2. Speed of US ICBMs and SLBLMs as a function of the year IOC obtained[46]

Figure 2 further shows how sequential versions of ICBMs and SLBMs did not appreciably increase their speed over the last 50 years. Instead, speed remained relatively constant or even decreased. Increasing speeds may not matter for prompt nuclear strikes since SLBMs and other shorter-ranged ballistic nuclear weapons can already strike targets very rapidly.[47] This graph also shows that current US hypersonic technology lags ICBM and SLBM technology in speed. So far, hypersonics is an evolutionary technology relative to the speed of existing ballistic nuclear weapon delivery systems.

Ballistic missiles have a much longer trajectory than hypersonic weapons, suggesting that raw speed is a poor comparison. James Acton et al. estimated that early warning satellites could provide up to 30 minutes of warning time for an attack by ICBMs and slightly longer in the case of boost-glide hypersonic weapons. While satellites might provide a much shorter (16 minute) warning against hypersonic cruise missiles, this time frame would be similar to the warning times provided against intermediate-range ballistic missiles.[48] SBLMs are estimated to be able to reach their targets in about five minutes in many scenarios.[49] NAHWs are unlikely to change warning times of the overall arsenal. Furthermore, it is difficult to see the strategic advantage of even faster attack times, especially considering the aforementioned analyses estimate it will take at least seven or eight minutes to notify the president of the United States of an impending nuclear attack. While there are other potential advantages to hypersonic delivery systems, there is little to gain by simply increasing speed relative to that of existing nuclear weapon delivery systems.

Another key component of a nuclear weapon delivery system is range. The historical evolution of cruise missiles, ICBMs, and SLBMs provides context for evaluating the range of potential hypersonic nuclear delivery systems. As seen in figure 3, the range of US ICBMs did not substantially increase over time. Since they could already cross continents, additional range improvements were gratuitous.[50] Technology did improve the relatively short ranges of US SLBMs, and they grew to eventually equal the range of US ICBMs. This development arguably increased the operational attack range of submarines, making them harder to find in a vast ocean and thereby increasing their survivability. Overall, historical technological changes in ICBM range were small while the range of SLBM technology increased steadily over time. However, current US hypersonic technology is dwarfed by existing ballistic technology in terms of range.

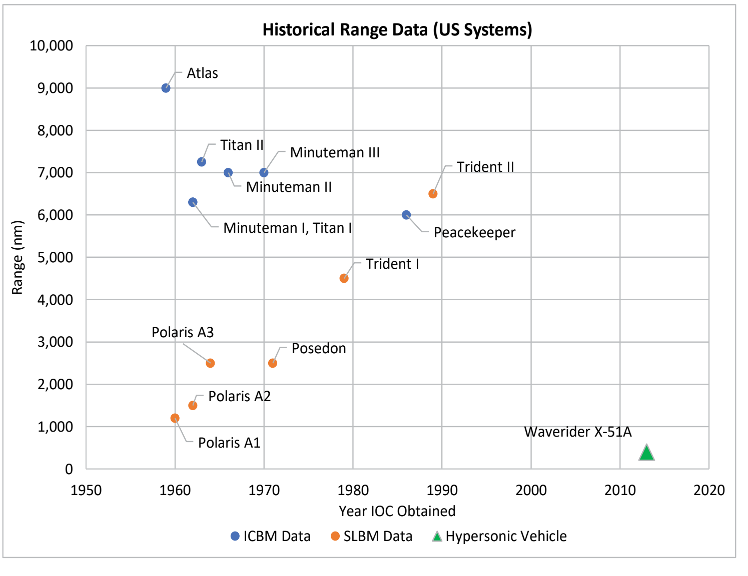

Figure 3. Range of US ICBMs as a function of the year IOC obtained[51]

One virtue of conventional hypersonic weapons is that they may be accurate enough to destroy individual vehicles, suggesting they may eventually provide significantly greater accuracy than provided by ICBMs. Increasing weapon accuracy by a factor of two is functionally equivalent to increasing yield by a factor of eight, meaning an accurate bomb is often better than a bigger bomb.[52] Missile accuracy is defined in terms of circular error probability (CEP), the range described by a circle within which a missile has a 50 percent probability of striking.[53] As figure 4 depicts, US ICBMs generally increased their accuracy through each technology upgrade. A similar analysis shows that Russian and Chinese ICBMs and SLBMs were characterized by evolutionary changes in speed, range, and accuracy.[54] While little data is available about US hypersonic delivery systems, the accuracy of ICBMs is significantly less than that of cruise missiles. Therefore, a NAHW will probably be significantly more accurate then ICBMs.

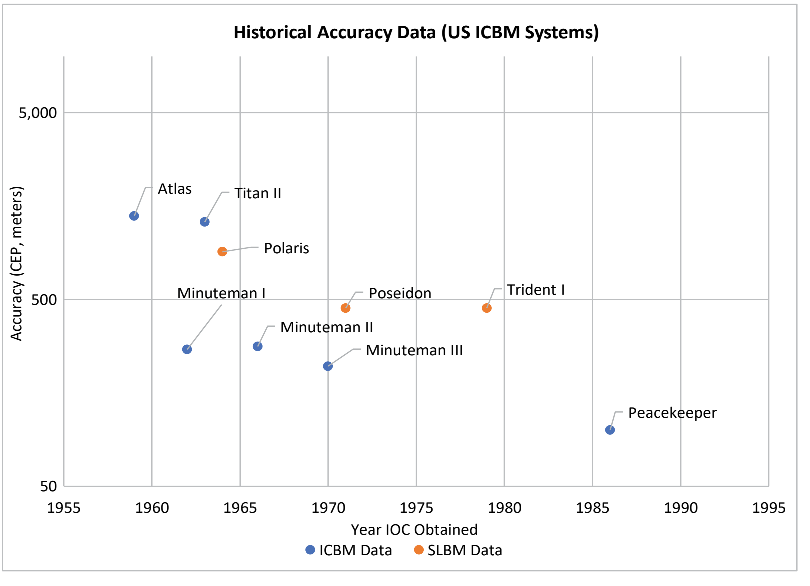

Figure 4. Accuracy of US ICBMs and SLBMs as a function of the year IOC obtained[55]

The range and speed of US ICBMs has been relatively stable over time.[56] US hypersonic missiles show little sign of leapfrogging ICBMs in terms of these parameters. However, hypersonic missiles will likely prove to be more accurate than ICBMs. On one hand, increasing the accuracy of a nuclear weapon delivery system by a few tens of meters may be inconsequential for strategic nuclear weapons with blast radii measured in miles. On the other hand, increased accuracy allows smaller-yield nuclear warheads to be considered for various missions. Accuracy is an important characteristic of cruise missiles, the next element considered in our model of NAHWs.

Cruise Missiles

Figure 5 shows the range of cruise missiles as a function of the year they obtained IOC. The range of cruise missiles has remained relatively fixed over the last 70 years. While limited range presents some operational constraints, many cruise missiles are released from mobile platforms like ships or aircraft capable of independently maneuvering close to their targets. Historically, acquiring bases close to the Soviet Union was an important consideration in overcoming the range limits of aircraft. In any case, the current unclassified range of hypersonic weapons is well within the range of existing cruise missiles. From the perspective of range, NAHWs are an evolution—rather than a revolution—relative to cruise missiles.

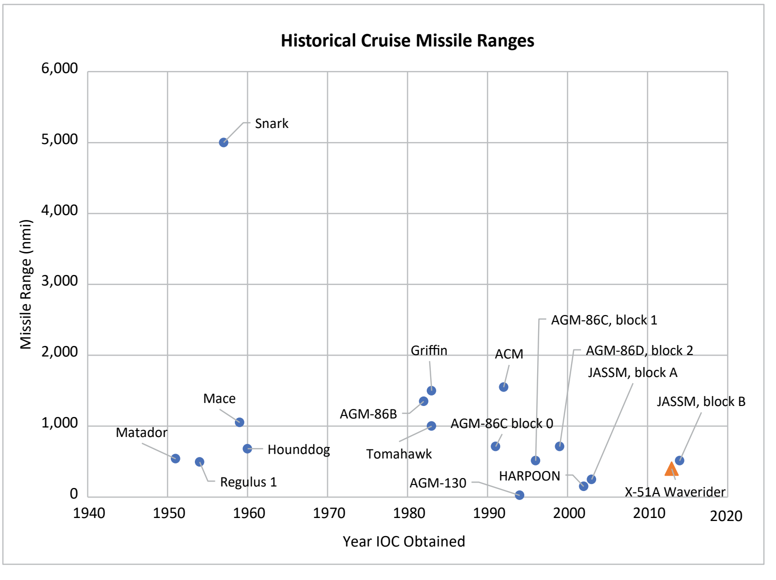

Figure 5. Range of US cruise missiles as a function of the year IOC obtained[57]

Figure 6 shows that US cruise missiles have operated at speeds of less than Mach 2 for the last 50 years. Figure 6 contains fewer data points than figure 5 because the operational speed of several current US missiles remains classified.[58] It should be noted that this data compares an experimental test system (X-51A) to operational systems, an inevitable limitation since hypersonic weapons have not been fielded. Also, the classified nature of most recent cruise missile data may mask a recent evolution in cruise missile technological capability. However, while hypersonic missile speeds exceed the known speeds of existing cruise missiles, the reported speed of some hypersonic weapons is still considerably slower than for ICBMs.

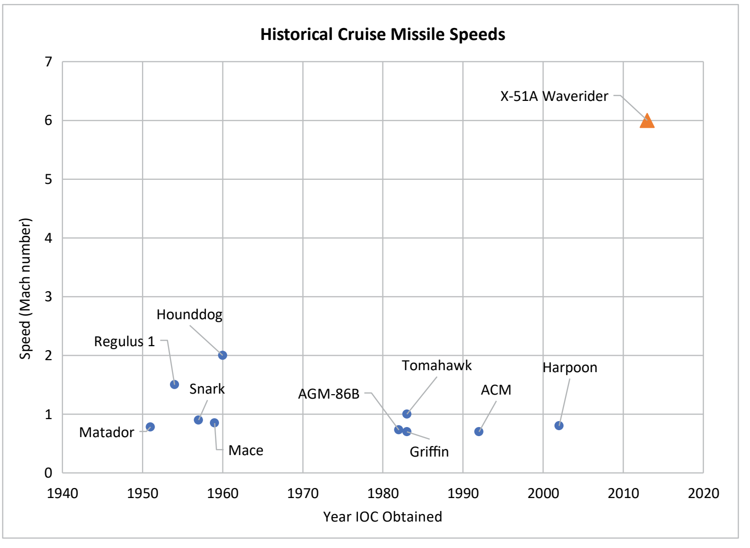

Figure 6. Speed of US cruise missiles as a function of the year IOC obtained[59]

While little data is available on the accuracy of cruise missiles, a comparison between figure 4 and figure 7 (below) shows that the accuracy of cruise missiles is much greater than for ICBMs and that cruise missile accuracy increased over time. However, as with nuclear weapons, it is unclear why increases in accuracy on the order of meters might prove decisive with weapons whose blast radius is measured in kilometers.

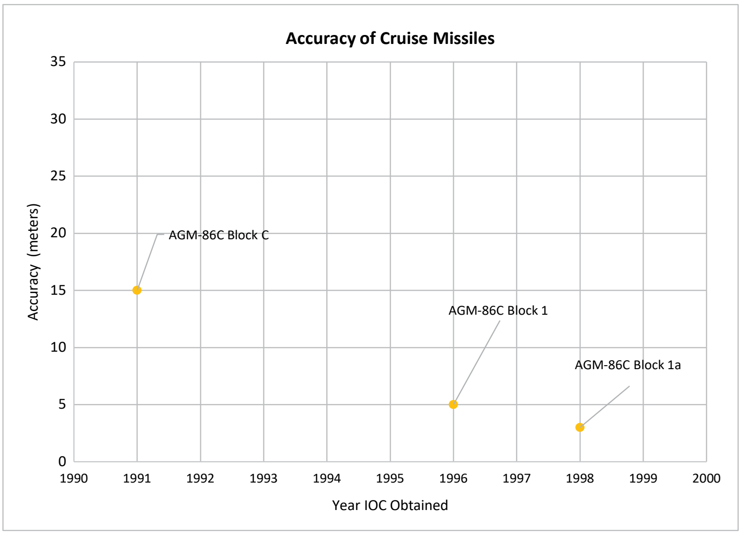

Figure 7. Accuracy of US cruise missiles as a function of the year IOC obtained[60]

As shown in the previous graphs, technology to improve the speed, range, and accuracy of ICBMs and cruise missiles took years or even decades to develop. This growth is an evolution compared to how nuclear weapons increased bomb yields by a factor of 700 over the course of a few years.[61] This revolutionary improvement dramatically changed national strategies and policies. Even though it has been researched for decades, hypersonic technology has not yet leapfrogged existing nuclear missile delivery technology. This suggests that hypersonic technology is not revolutionary. Therefore, a NAHW can be described using existing deterrence thinking. This does not imply that hypersonic technology is meaningless. As discussed earlier, technology evolution is an important part of nuclear weapon delivery system technology. The evolutionary nature of hypersonics is simply a strong argument that coupling nuclear weapons with hypersonic delivery vehicles is consistent with historical technological developments and with current US thinking about nuclear deterrence.

In terms of range, speed, and accuracy, sequential versions of ICBMs are best described by evolutions in technical capability rather than by revolutions in technology. In terms of range and speed, hypersonic technology did not leapfrog the capabilities of existing ICBMs and cruise missiles in three of the four metrics used in this study. The individual strategically relevant component technologies have been evolving slowly. Furthermore, the component technologies will likely combine in a linear way to form NAHWs. Therefore, NAHWs are an evolution relative to existing nuclear delivery technology. Using hypersonic technology for nuclear weapon delivery may provide strategic advantages, but it will likely not prove to be destabilizing.

Missile Defense

Hypersonic technology is remarkable because it provides another means to improve missile survivability. The combination of speed and maneuverability may give hypersonic weapons the potential to mitigate existing missile defense technologies. Missile defenses need time to observe a launch, deduce the object is a missile, classify the missile flight parameters, distinguish the missile from decoys or other noise, and continue tracking.[62] Hypersonic systems reduce the amount of time available for all of these tasks. In the case of a ballistic missile, once the defender has identified it as such, it has a good idea of where the missile is going and can use that knowledge to cue midcourse and terminal defenses. Since hypersonic weapons are maneuverable, defenders are not sure which of their systems will be positioned to defeat the incoming missile.

However, early nuclear cruise missiles, such as the Snark, were vulnerable to antiaircraft fire.[63] After cruise missiles sank an Israeli destroyer in 1967, the US began to develop antimissile ship defense.[64] Air defenses motivated Britain to move from a bomber-based to a missile-based nuclear force.[65] Congress authorized the first US ballistic missile defense system in 1969.[66] ICBM designs and tactics dealt with the problem of survivability by incorporating decoys, chaff, alternate trajectories, radiation hardening, electronic countermeasures, and launch-on-warning postures.[67] Multiple independently targetable reentry vehicle (MIRV) systems packing multiple warheads onto a single missile were another response to missile defense technology.[68] These examples show how missiles and missile defense technology tended to coevolve.

From a historical point of view, hypersonic delivery systems for nuclear weapons can be viewed as a response to a long line of developments in the competition between missiles and missile defense. Technology advancements often provided an evolutionary technological edge, but the temporary advantage lasted only until a compensating technology was developed. While hypersonic weapons again promise that the missile will always get through, history suggests that new defenses against them will eventually thwart these new technologies. NAHWs are unlikely to prove revolutionary enough to catalyze the development of a new class of deterrence thinking.

This analysis assumed hypersonic delivery technology to be a linear combination of its constituent elements. This assumption is justified as there is a significant overlap in missile defense against cruise missiles and missile defense against ICBMs. This point is important because it suggests that hypersonic weapons are a combination of cruise missiles and ICBMs. Since defenses against both ICBMs and cruise missiles exist, it seems reasonable that defenses against hypersonics are quite possible.

According to the latest US *Missile Defense Review*, multiple missile defense systems are capable of defending against a mix of ballistic and cruise missile threats. For example, the Patriot PAC-3 missile defense system is capable of defending against cruise missiles and short-range ballistic missiles.[69] The F-35 is currently capable of defending against cruise missiles, and there are plans to include a capability to defend against boost-phase ballistic missiles.[70] The SM-6 missile of the Aegis system is also capable of defending against both ballistic and cruise missiles.[71] Since several existing systems can defend against cruise and ballistic missiles, it is reasonable to expect that future systems will be capable of defending against missiles that are a combination of the two.

The reason that existing missile defense systems can defend against cruise and ballistic missiles is that the dividing line between them is ambiguous.[72] While there are clear differences, there are significant similarities. For example, short-range ballistic missiles spend a significant portion of their time in the atmosphere and have more aerodynamic features than longer-range missiles that spend more of their flight time in space.[73] Furthermore, ballistic missiles and cruise missiles generally have a similar flight path in the terminal phase. This is important because many missile defense systems are designed to attack missiles in their terminal phase.

Finally, ballistic missiles do not always follow a completely ballistic trajectory. When Terminal High Altitude Area Defense missiles execute an energy management maneuver to burn fuel as required for short-range engagements, the missile executes a very non-ballistic loop.[74] MIRV weapons are designed to attack multiple targets, demonstrating that a limited maneuvering capability has previously been incorporated into ballistic missile delivery systems. Since maneuverability is possible in some ballistic missiles, maneuverable NAHWs can be viewed as an evolution in ICBM technology rather than as a revolution.

One final evidence of the evolutionary nature of NAHW technology is the fact that missile defenses for hypersonic weapons are already being developed. The 2019 US *Missile Defense Review* states that the US is currently working on developing systems to defeat hypersonic weapons.[75] DARPA's recently announced Glide Breaker project is one example.[76]

This analysis has shown that NAHWs will constitute an evolution rather than a revolution in technology. Missile defense technology is capable of defending against maneuverable weapons such as cruise missiles and high-speed threats such as ICBMs. Reasonably, it follows that missile defense technology may evolve to address weapons like NAHWs that combine both capabilities.

Implications for Both Sides Having Weapons

In terms of speed, range, accuracy, and missile defense, there seem to be few differences between both sides having NAHWs and both sides having significant numbers of ICBMs, SLBMs, and nuclear-armed cruise missiles. Missile defense is incapable of defeating the hundreds of nuclear weapons in the Chinese arsenal, much less the thousands of nuclear weapons possessed by the US and Russia. NAHWs do not increase the first-strike advantage against powers with large, diverse nuclear arsenals. Even if a hypersonic weapon successfully defeats existing missile defenses and delivers a nuclear weapon, China, Russia, and the US can still deliver an overwhelming retaliatory strike.

Acton and others suggest that conventional hypersonic weapons introduce significant risks specific to these fast, maneuverable missile weapons.[77] The risk that a conventional attack is confused with a nuclear strike (warhead ambiguity) and the risk that a country mischaracterizes an attack on a neighbor as an attack on itself (destination ambiguity) should be considered in terms of the relative level of risk posed by other legs of the nuclear triad.[78] Deploying NAHWs while simultaneously deploying conventional hypersonic weapons may significantly exacerbate concerns regarding warhead and destination ambiguity. However, US bombers were capable of carrying both nuclear and conventional weapons as early as 1956.[79] The current US aircraft fleet also includes dual-capable aircraft.[80] The US believes that Russia has a "large, diverse, and modern" set of dual-capable weapon systems.[81] Likewise, bombers and cruise missiles can change course, meaning they have the potential for destination ambiguity, although their smaller speeds make this less of a concern. Dual-capable bombers have long been part of the strategic environment without proving hugely destabilizing, suggesting that warhead ambiguity may not be an issue for NAHWs.

Conclusion

This article examined whether a future NAHW can be understood by existing deterrence logic by considering hypersonic weapons as an evolution in nuclear weapon delivery technology. The analysis considered a NAHW to be a superposition of existing technologies analogous to hypersonic missiles: ICBMs, cruise missiles, and missile defense. The advancement of each of these systems was analyzed through the perspective of historical development and compared with unclassified information describing hypersonic systems. Key quantitative parameters such as range, speed, and accuracy were used alongside more qualitative data. Analyzing these analogous technologies suggests that the relevant elements of hypersonic technology will evolve slowly enough to remain consistent with existing thinking about nuclear deterrence.

There are several limitations of this study. First, operational data on hypersonic systems and their capabilities (range, speed, and accuracy) are not widely available because these systems are still under development and potentially classified. As more information on operational hypersonic systems comes available, it is possible that new systems may provide notable improvements relative to existing nuclear weapon delivery systems. Second, by comparing hypersonic weapons to existing systems, we implicitly assumed that NAHWs will be used the same way as existing systems and ignored the possibility that NAHWs might be used differently. In novel applications, range, speed, accuracy, and avoiding missile defenses may not be paramount considerations. As Kissinger pointed out, technology is not everything. Instead, real advantages stem from "subtler and more discriminating uses rather than adding to [weapon] power or speed."[82] Perhaps this is the case with hypersonic weapons. This does not imply that hypersonic delivery systems are a useless military innovation. The risks of nuclear retaliation described by nuclear deterrence are more relevant to nuclear weapons than to conventional weapons.

However, policy makers do not have the luxury of choosing a development path based on a perfect, full-fledged knowledge of future fielded systems and how they will be used. Other authors have investigated the ways hypersonic technology may shape strategy and policy. For example, in their *War on the Rocks* commentary, Heather Venable and Clarence Abercrombie predict that hypersonic technology will face technological countermeasures and will not be destabilizing.[83] On the other hand, nuclear strategy and emerging technology researcher Alan Cummings argues that simply having the capability to launch rapid strikes may provide strategic advantages.[84] The Defense Intelligence Agency director predicts that "developments in hypersonic propulsion will revolutionize warfare by providing the ability to strike targets more quickly, at greater distances, and with greater firepower."[85]

Our analysis uses existing systems and operational concepts as a starting point to consider the policy implications of NAHWs. While NAHWs may evade missile defense systems in small numbers, ICBMs will probably defeat missile defense systems if used in large numbers.[86] NAHWs cannot prevent nuclear reprisal by Russia or China unless they are used as part of a massive first strike capable of destroying adversary second-strike capability. In terms of missile defense, a large salvo of NAHWs is nearly identical to a large salvo of ICBMs as both may overwhelm a missile defense system, suggesting NAHWs offer little advantage for large-scale nuclear strike missions relative to ICBMs or SLBMs. Even if revisionist powers possess highly robust defenses against existing ICBMs and nuclear-armed cruise missiles, their nuclear arsenals are too small to offer a credible second-strike capability, suggesting NAHWs offer little advantage.

One way that NAHWs may tangibly affect US deterrence policy is in their potential role for "tactical" nuclear weapons, otherwise known as low-yield nuclear weapons. The 2018 *NPR* discusses the need for having a flexible option and ensuring that there is no adversarial misperception about US capabilities. Hypersonic nuclear weapon delivery systems may provide advantages for delivering tactical nuclear weapons.[87] Consider a scenario in which a small "tactical" nuclear warhead is employed to destroy a difficult target with only minimal collateral damage. If nuclear weapons are viewed as gargantuan classical bombs, tactical nuclear weapons are simply another form of war fighting in which accuracy is extremely important. Cruise missiles are more accurate than ICBMs, and so cruise missiles might be more useful than ICBMs for highly precise nuclear strikes. Since cruise missiles are more vulnerable to missile defenses than are hypersonic delivery systems, a NAHW may be advantageous relative to existing weapons for tactical nuclear strikes.

However, nuclear weapons are not simply bigger, more effective conventional bombs.[88] Tactical nuclear weapons carry a risk of nuclear retaliation if used against a nuclear-armed adversary. Extended deterrence suggests there is a risk of nuclear retaliation if nuclear weapons are used against a nation allied to a nuclear power. The risk of retaliation by a nuclear superpower is not mitigated by using a NAHW to "guarantee" successful delivery of a small number of tactical nuclear weapons because the arsenals of the world's great powers are probably too large and diverse to allow a successful first strike.[89] Using a NAHW against a nation possessing a small nuclear arsenal only provides an advantage if the adversary also retains an effective missile defense system. Otherwise, nuclear-armed cruise missiles or nuclear-armed ballistic missiles are presumably equally as effective as NAHWs.

There appears to be little advantage to upgrading the existing US nuclear arsenal to include hypersonic delivery systems. Based on the research conveyed in this article, one conclusion is that there is little advantage to upgrading the existing US nuclear arsenal to include hypersonic delivery systems as their advantages in speed, range, and accuracy are on the margins and the monies required may be better used elsewhere. A NAHW provides few advantages relative to cruise missiles or ICBMs in terms of speed, range, or accuracy. While hypersonic delivery systems appear to provide some capability to defeat missile defense systems, this potential advantage may only be temporary—especially if current efforts to develop missile defenses against hypersonic weapons continue.

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Notes

1. John A. Tirpak, "The Great Hypersonic Race, *Air Force Magazine*, 27 June 2018, http://www.airforcemag.com/.

2. John L. Dolan, Richard K. Gallagher, and David L. Mann, "Hypersonic Weapons: A Threat to National Security," *Real Clear Defense*, 23 April 2019, https://www.realcleardefense.com/.

3. Former CJCS Martin Dempsey said that the only way to defeat large salvos of ICBMs is through preemptive strikes, implying that missile defense is inadequate to deal with large salvos of missiles. Martin E. Dempsey, *Joint Integrated Air and Missile Defense: Vision 2020* (Washington, DC: The Joint Staff, 2013), 3, https://www.jcs.mil/. The *2019 Missile Defense Review* states that the US is "protected against a limited ICBM attack." Department of Defense, *2019 Missile Defense Review* (Washington, DC: Office of the Secretary of Defense, 2019), X, https://www.defense.gov/. President Bush viewed ballistic missile defense as necessary to protect the United States against rogue nations and terrorists, emphasizing the utility of ballistic missile defense against small salvos of ICBMs. See, for example, Terence Neilan, "Bush Pulls Out of ABM Treaty; Putin Calls Move a Mistake," *New York Times*, 13 December 2001, https://www.nytimes.com/. Lawrence Freedman makes a similar observation in his book *Deterrence* (Malden, MA: Polity Press, 2004), 37.

4. Richard H. Speier, George Nacouzi, Carrie A. Lee, and Richard M. Moore, *Hypersonic Missile Proliferation: Hindering the Spread of a New Class of Weapons* (Santa Monica, CA: RAND Corporation: 2017), xii, https://www.rand.org/; and Kyle Mizokami, "China Conducts New Hypersonic Weapons Test," *Popular Mechanics*, 7 August 2018, https://www.popularmechanics.com/.

5. James Acton, *Silver Bullet? Asking the Right Questions about Conventional Prompt Global Strike* (Washington, DC: Carnegie Endowment for Peace, 2013), https://carnegieendowment.org/; Eleni Ekmektsioglou, "Hypersonic Weapons and Escalation Control in East Asia," *Strategic Studies Quarterly* 9, no. 2 (Fall 2015): 43–68, https://www.airuniversity.af.edu/; Joshua H. Pollack, "Boost-Glide Weapons and US-China Strategic Stability," *Nonproliferation Review* 22, no. 2 (2015): 155, published online February 2016, https://doi.org/10.1080/10736700.2015.1119422; and Speier et al., *Hypersonic Missile Proliferation*, iii.

6. Ekmektsioglou examines how China might perceive US conventional hypersonic weapons as a threat to its nuclear forces and discusses ways China might respond. Speier

et al. also consider the impacts of proliferating hypersonic technology. Acton considers the relevant missions of conventional hypersonic weapons, as well as various modes of instability they might prompt. Ekmektsioglou, "Hypersonic Weapons," 43–68; and Speier et al., *Hypersonic Missile Proliferation*; and Acton, *Silver Bullet?*

7. Acton, *Silver Bullet?*, 5–7; Ekmektsioglou, "Hypersonic Weapons," 43; and Pollack, "Boost-Glide Weapons," 155. However, this definition technically includes ICBMs and SLBMs as hypersonic weapons because they travel faster than Mach 5. See, for example, Office of the Secretary of Defense, *Nuclear Posture Review* (Washington, DC: Department of Defense, 2018), 45, https://media.defense.gov/.

8. Andrew Knoedler, "Hypersonic Air-Breathing Weapon Concept (HAWC)," Defense Advanced Research Projects Agency, accessed June 2019, https://www.darpa.mil/.

9. We examined the rate of change of specific technology areas by reviewing the number of publications reporting advances in each technology as a function of time. We considered three technology groups: scramjet engines, high-temperature hypersonic materials, and hypersonic aerodynamic structures. Beginning with 1960 data, we counted the number of journal publications, patents, and conference materials for each of the six search term sets. We chose 1960 as the start date to correspond to the ICBM and cruise missile data shown later in the article. Advanced manufacturing was not included because this technology is broad enough to apply to many other technologies. We queried the EBSCO database using the following six sets of search terms: (1) "hypersonic," (2) "hypersonic flight," (3) "high temperature" and "hypersonic" and "material," (4) "hypersonic" and "vehicle configuration," (5) "scramjet" or "supersonic ramjet" or "hypersonic propulsion," and (6) "hypersonic aerodynamics." The first two search terms were included to account for general trends in overall hypersonic research.

10. For a brief description of the X-20 project, see Jay Miller, *The X-Planes, X-1 to X-45* (Midland, MI: Midland Publishing, 2001), 231–39; for a brief description of the X-24 project, see 261–71. Examining the number of patents filed referencing the aforementioned search terms shows a similar story. A similar analysis of the record of conference materials shows a more ambiguous story. However, journal articles are more likely to be peer reviewed than conference materials. Patents are expensive to acquire and renew. Therefore, journal publications and patents probably show a more reliable summary of the evolution of hypersonic component technology than conference materials. There are limitations to analyzing this type of metadata because the search technique does not assess the relative quality of the research. Large technology advances are weighted equally with small advances, and flawed analyses are counted the same as sound ones. The data shows significant previous interest in hypersonic technology in the 1960s and 1970s. These short but intense explosions in research correspond to the development of the X-20—also known as the Dyna-Soar project—and the X-24. The X-20 was cancelled in December 1963, and the X-24's last flight was in 1975. Even though the X-20 was never built into a flight-test-capable model and the X-24 never achieved speeds of greater than Mach 1.8, both projects tremendously advanced the state of the art of hypersonic research. Developments of hypersonic technology over the last two decades may be the result of researchers building off a single large technology breakthrough. Or this increase in research could simply be mirroring greater government interest and/or funding.

11. Bernard Brodie, "The Absolute Weapon: Power and World Order," in *War in the Atomic Age*, ed. Bernard Brodie (New Haven, CT: Yale University Institute of International Studies, 1946), 25. Brodie cites a post–World War II survey study suggesting it

would have taken 730 bombers to do the same damage done by the one nuclear bomb dropped on Hiroshima.

12. Brodie, 76.

13. Thomas C. Schelling, *Arms and Influence* (New Haven, CT: Yale University Press, 2008), 24–27.

14. Glenn H. Snyder, *Deterrence and Defense: Toward a Theory of National Security* (Princeton: Princeton University Press, 1961), 15; see also Brodie, "The Absolute Weapon," 76.

15. Schelling, *Arms and Influence*, 166–68. Kissinger reached a similar conclusion; see Henry Kissinger, *Nuclear Weapons and Foreign Policy* (New York: Harper & Brothers, 1957), 48. Rosemary Foot concedes that while nuclear deterrence wasn't central to ending the conflict, nuclear threats were a significant factor. Rosemary J. Foot, "Coercion and Ending the Korean War," *International Security* 13, no. 3 (Winter 1988–89): 92–112.

16. Robert Anthony Pape, *Bombing to Win: Air Power and Coercion in War* (Ithaca, NY: Cornell University Press, 1996), 6–11.

17. Kissinger, *Nuclear Weapons*, 13–14.

18. Dietrich Schroeer, *Science Technology and the Nuclear Arms Race* (New York: John Wiley & Sons, 1984), 110–12, 115.

19. See figure 2 and its associated references.

20. Schroeer, *Science Technology*, 151. See also Ronald Huisken, *The Origin of the Strategic Cruise Missile* (New York: Praeger Publishers, 1981), 16; and Keir A. Lieber and Darryl G. Press, "The New Era of Counterforce: Technological Change and the Future of Nuclear Deterrence," *International Security* 41, no. 4 (Spring 2017): 24, https://doi.org/.

21. Huisken, *Origin of the Strategic Cruise Missile*, 9–10, 16–17; and Ted Nicholas and Rita Rossi, *U.S. Missile Data Book*, vol. 1, 36th ed. (Huntington Beach, CA: Data Research Associates, 2012), tables 1-2 and 3-2.

22. Schroeer, *Science Technology*, 114–15.

23. Schroeer, 109.

24. Thomas G. Mahnken, *The American Way of War* (New York: Columbia University Press, 2008), 30; and Schroeer, *Science Technology*, 107.

25. Schroeer, 201.

26. Lieber and Press, "New Era of Counterforce," 16.

27. Lieber and Press, 10.

28. See Ronald L. Tammen, *MIRV and the Arms Race: An Interpretation of Strategy* (New York: Praeger, 1973), 85–86.

29. For a review of how deterrence thinking evaluated missile defense, see Ashton B. Carter and David N. Schwartz, eds., *Ballistic Missile Defense* (Washington, DC: Brookings Institution, 1984).

30. Kissinger, *Nuclear Weapons*, 17–18, 120.

31. Kissinger, 119.

32. Kissinger, 126.

33. Kissinger, 120. Herman Kahn made similar arguments that a "symmetrical" use of nuclear weapons would be more advantageous for China than for the US. See Herman Kahn, *On Thermonuclear War* (Piscataway, NJ: Transaction Publishers, 2007), 505.

34. Kissinger, *Nuclear Weapons*, 122–23.

35. Kissinger, 124, 185, 199.

36. Kissinger, 120.

37. Kissinger, 123.

38. Kissinger, 16–17.

39. Colin Gray, "Nuclear Deterrence and Technological Change: Retrospect and Prospect," in *On the Logic of Nuclear Terror*, ed. Roman Kolkowicz (Winchester, MA: Allen & Unwin, Inc., 1987), 155–85.

40. Office of the Secretary of Defense, *Nuclear Posture Review*, II, VII.

41. Peter J. Mantle, *The Missile Defense Equation* (Reston, VA: American Institute of Aeronautics and Astronautics, 2004), 10.

42. Acton points out the range of some planned hypersonic weapons is at least 5,000 miles Acton, *Silver Bullet?,* 78.

43. Mantle, *Missile Defense Equation*, 10.

44. Lieber and Press, "New Era of Counterforce," 16.

45. For a review of ballistic missile defense technology, see National Research Council, *Making Sense of Ballistic Missile Defense: An Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison with Other Alternatives* (Washington, DC: National Academies Press, 2012), https://www.nap.edu/; and Ashton B. Carter, "BMD Applications: Performance and Limitations," in Carter and Schwartz, *Ballistic Missile Defense*, 124–29.

46. The graph was developed from Nicholas and Rossi, *U.S. Missile Data Book*, tables 1-2 and 3-2; Schroeer, *Science Technology*, 176; and Jonathan E. Medalia, *Strategic Forces: MX ICBM* (*Weapons Facts*), Report no. 1884046 [Washington, DC: Congressional Research Service, August 1987], 1. Hypersonic data comes from US Air Force, "X-51A Waverider," fact sheet, 2 March 2011, https://www.af.mil/.

47. SLBMs travel at roughly the same speed as ICBMs but can be fired from much closer, suggesting they can be significantly more prompt than ICBMs.

48. Acton, *Silver Bullet?*, 68–70.

49. Speier et al., *Hypersonic Missile Proliferation*, 16. Other studies estimate nine minutes of warning time. See Lisbeth Gronlund and David C. Wright, "Depressed Trajectory SLBMS: A Technical Evaluation and Arms Controls Possibilities," *Science and Global Security* 3, nos. 1–2 (1992): 110, 117.

50. Kissinger, *Nuclear Weapons*, 119.

51. The graph was developed from Nicholas and Rossi, *U.S. Missile Data Book*, tables 1-2 and 3-2; and Schroeer, *Science Technology*, 176. However, Nicholas and Rossi report the speed of the Peacekeeper as Mach 4, inconsistent with information provided by other sources. See National Museum of the US Air Force, "Martin Marietta LGM-118A Peacekeeper," fact sheet, 13 July 2015, https://www.nationalmuseum.af.mil/. The database "Military Periscope" also reports the speed as approximately Mach 20. See "Military Periscope," accessed April 2019, https://www.militaryperiscope.com/. Both estimates convert to a Mach number by assuming the speed of sound is approximately 767 miles per hour. A speed of Mach 20 is used for the graph. For hypersonic data, see US Air Force, "X-51A Waverider."

52. Schroeer, *Science Technology*, 202.

53. Schroeer, 144.

54. For example, the Russian SS-11 (mod 2) had a range of 13,000 km in 1973. In 1988, the SS-18 (mod 6) had a range of 16,000 km. Several other variants including the SS-17, SS-19, SS-24, SS-25 and several variants of the SS-18 had shorter ranges than the SS-11 (mod 2). The range difference between SBLBs increased from 7,800 km in

1973 (SS-N-8) to 8,300 km in 1985 (SS-N-23). Again, several intermediate variants had less range than the SS-N-8. The accuracy of Russian ICBMs decreased from 1,675 meters CEP in 1973 (SS-13 mod 2) to 200 meters in 1987 (SS-24). See Thomas B. Cochran, William M. Arkin, Robert S. Norris, and Jeffrey I. Sands, *Nuclear Weapons Databook*, vol. 4, *Soviet Nuclear Weapons* (New York: Harper & Row, 1989), 111, 114; and Schroeer, *Science Technology*, 56, 63–65, 68–72.

55. The graph was developed from Nicholas and Rossi, *U.S. Missile Data Book*, tables 1-2 and 3-2; and Schroeer, *Science Technology*, 176. For information on the accuracy of the Atlas missile including CEP, see "SM-65 Atlas," GlobalSecurity.org, accessed 24 February 2019, https://www.globalsecurity.org/. Note the *Air and Space Power Journal* (*ASPJ*) article citing the accuracy of 10 miles but not indicating whether this indicates CEP. See *ASPJ* staff, "Atlas: The Godfather of ICBMs and Space-Launch Vehicles," *Air and Space Power Journal* 17, no. 1 (Spring 2003): 68, https://www.airuniversity.af.edu/. For cruise missile data, see National Museum of the US Air Force, "Martin TM-61A Matador," fact sheet, 29 May 2015, https://www.nationalmuseum.af.mil/; National Museum of the US Air Force, "Martin CGM-138 Mace," 29 May 2015, https://www.nationalmuseum.af.mil/; US Air Force, "AGM-86B/C/D Missiles," fact sheet, 24 May 2010, https://www.af.mil/; and US Air Force, "AGM-130 Missile," fact sheet, 18 June 2003, https://www.af.mil/. For hypersonic data, see US Air Force, "X-51A Waverider."

56. In one way, this is not surprising because the physics of ballistics make the range physically dependent on the speed of the missile. For a discussion of this, see, for example, app. C in Mantle, *Missile Defense Equation*.

57. The graph was developed from US Air Force, "AGM-86B/C/D Missiles"; US Air Force, "AGM-130 Missile"; IHS Jane's, *IHS Jane's Weapons: Strategic* (Coulsdon, Surrey: IHS Global, 2013), 155–56; and Missile Defense Project, "JASSM/JASSM ER (AGM-158A/B)," *Missile Threat*, Center for Strategic and International Studies, 6 October 2016, last modified 15 June 2018, https://missilethreat.csis.org/

58. See US Air Force, "AGM-86B/C/D Missiles"; and US Air Force, "AGM-130 Missile."

59. The graph was developed from National Museum of the US Air Force, "Martin TM-61A Matador"; Museum of the US Air Force, "Martin CGM-13B Mace," fact sheet, 29 May 2015, https://www.nationalmuseum.af.mil/; US Air Force, "AGM-86B/C/D Missiles"; and US Air Force, "AGM-130 Missile." For hypersonic data, see US Air Force, "X-51A Waverider."

60. The graph was developed from Nicholas and Rossi, *U.S. Missile Data Book*, tables 1-2 and 3-2; US Air Force, "AGM-86B/C/D Missiles"; National Museum of the US Air Force, "Martin TM-61A Matador"; and National Museum of the US Air Force, "Martin CGM-13B Mace."

61. Brodie, "The Absolute Weapon," 25.

62. Mantle, *Missile Defense Equation*, 174–75.

63. Huisken, *Origin of the Strategic Cruise Missile*, 16–17. While cruise missiles are not hypersonic, they are maneuverable. Maneuverability is what makes hypersonic weapons different from ICBMs.

64. Huisken, 29.

65. Lawrence Freedman, "The Small Nuclear Powers," in Carter and Schwartz, *Ballistic Missile Defense*, 253.

66. Schroeer, *Science Technology*, 236.

67. See Tammen, *MIRV and the Arms Race,* 85–86.

68. Alexey Arbatov and Vladimir Dvorkin, "The Impact of MIRVs and Counterforce Targeting on the US-Soviet Strategic Relationship," in *The Lure and Pitfalls of MIRVs*, eds. Wheeler Krepon, Travis Wheeler, and Shane Mason (Washington, DC: Stimson Center, 2016), 70–71, https://www.stimson.org/; Jeffrey G. Lewis, "China's Belated Embrace of MIRVs," in Krepon, Wheeler, and Mason, *Lure and Pitfalls of MIRVs*, 95, 100, 110; and Lawrence Freedman, "The First Two Generations of Nuclear Strategists," in *Makers of Modern Strategy: From Machiavelli to the Nuclear Age*, eds. Peter Paret, Gordon Alexander Craig, and Felix Gilbert (Princeton, NJ: Princeton University Press, 1986), 759–60. While Tammen suggests MIRVs are a response to ballistic missile defense technology, he indicates there were other motivations as well. Tammen, *MIRV and the Arms Race*, 104, 107, 113–14, 137.

69. See Department of Defense, *2019 Missile Defense Review*, 50, where air-breathing weapons refer to cruise missiles.

70. Department of Defense, 55.

71. Department of Defense, 48, 53.

72. Mantle, *Missile Defense Equation*, 8–16.

73. Mantle, 11–12.

74. Mantle, 13.

75. Department of Defense, *Missile Defense Review*, XIV, XVIII.

76. Tom Porter, "What Are Hypersonic Weapons and Why Is DARPA So Concerned about Stopping Them?," *Newsweek*, 13 November 2018, https://www.newsweek.com/.

77. In addition to the Acton references later in this paragraph, see Speier et al., *Hypersonic Missile Proliferation*, 8.

78. Acton, *Silver Bullet?*, 111–18.

79. "Telegram from the North Atlantic Council Ministerial Meeting to the Department of State," 14 December 1956, doc. 51, in *Foreign Relations of the United States, 1955–1957,* vol. 4*, Western European Security and Integration*, ed. William Z. Slany (Washington, DC: Government Printing Office, 1988), https://www.history.state.gov/.

80. Office of the Secretary of Defense, *Nuclear Posture Review*, II, X, 16, 49.

81. Office of the Secretary of Defense, 49.

82. Kissinger, *Nuclear Weapons*, 120.

83. Heather Venable and Clarence Abercrombie, "Muting the Hype over Hypersonics: The Offense-Defense Balance in Historical Perspective," *War on the Rocks*, 28 May 2019, https://warontherocks.com/.

84. Alan Cummings, "Hypersonic Weapons: Tactical Uses and Strategic Goals," *War on the Rocks*, 12 November 2019, https://warontherocks.com/.

85. Robert Ashley, "Statement for the Record: Worldwide Threat Assessment," Statement before Senate Armed Services Committee, Washington, DC, 6 March 2018, https://www.dia.mil/.

86. See Dempsey, *Vision 2020*, 3; Department of Defense, *2019 Missile Defense Review*, X; Neilan, "Bush Pulls Out of ABM Treaty"; and Freedman, *Deterrence*, 37.

87. See Kahn, *On Thermonuclear War*, 16. Others who believe nuclear weapons are useful for war fighting include Russian and US military planners who incorporate low-yield nuclear weapons into their military arsenals. See Office of the Secretary of Defense, *Nuclear Posture Review*, 22, 53–54. Freedman argued tactical nuclear weapons could be useful for war fighting by attacking logistical or other forces deep inside enemy territory;

see *The Evolution of Nuclear Strategy*, 106–8. Other scholars argue nuclear weapons have little military utility for directly attacks enemy military forces. For example, see Pape, *Bombing to Win*, 13–15, 49. Tactical nuclear weapons delivered via maneuverable hypersonic weapons will not prove any more or less destabilizing than tactical nuclear weapons delivered by other means.

88. For example, nuclear weapons are considered a weapon of mass destruction, distinguishing them from conventional weapons.

89. One counterargument is Ashton Carter's "ragged defense" theory, suggesting that missile defense provides a first-strike advantage because second-strike forces will be decimated so badly that their ragged response will be effectively defeated by the aggressor's missile defense system. See Ashton B. Carter, "Introduction to the BMD Question," in Carter and Schwartz, *Ballistic Missile Defense*, 22. Along similar lines, Kahn argued increased defenses or evacuations provide first strikes an increased advantage. Kahn, *On Thermonuclear War*, 14. However, as the adversary nuclear force becomes larger and more diverse, the risk of a successful first strike decreases, mitigating any theorized advantages posited by the ragged defense theory.