

INTERCONTINENTAL BALLISTIC MISSILES

AND THEIR ROLE IN FUTURE NUCLEAR FORCES

National Security Report



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Summary

The United States currently has a triad of nuclear capabilities: land-based intercontinental ballistic missiles (ICBMs), submarine-launched ballistic missiles (SLBMs) carried by ballistic missile submarines (SSBNs), and air-launched nuclear weapons delivered by long-range bombers. This triad has played a key role in US security for decades, but all current nuclear delivery systems except the B-2 bomber will reach the ends of their lives between the late 2020s and the early 2040s.

The Department of Defense (DoD) has started programs for maintaining the bomber and SSBN forces, but it has only recently begun a program to sustain the ICBM force. Specifics on program cost, missile characteristics, basing mode, and planned size of the future ICBM force are still to be determined. Without ICBM recapitalization, the number of US strategic delivery vehicles will decline from 834 in 2015 to about 220 by 2040, as shown in Figure S-1.

Accepting a decline of the sort shown in the figure would require a major change in US policy, whereas avoiding this decline would require a substantial increase in funding for this mission area. This report presents analytic results to help inform decisions on whether to retain an ICBM force beyond about 2035 and, if ICBMs are to be retained, which characteristics would be desirable in a future ICBM force. In this work we used physics-based modeling to consider survivability against preemptive counterforce attacks and looked at many different force structure options. Specifically, we evaluated seven triads (with 150 to 510 ICBMs and 8 to 12 SSBNs) and four bomber-SSBN dyads (with 10 to 18 SSBNs) in the context of a major nuclear war. Through this analysis we compared target coverage, ICBM survivability, the enemy’s price to attack, and the cost of each force structure option.

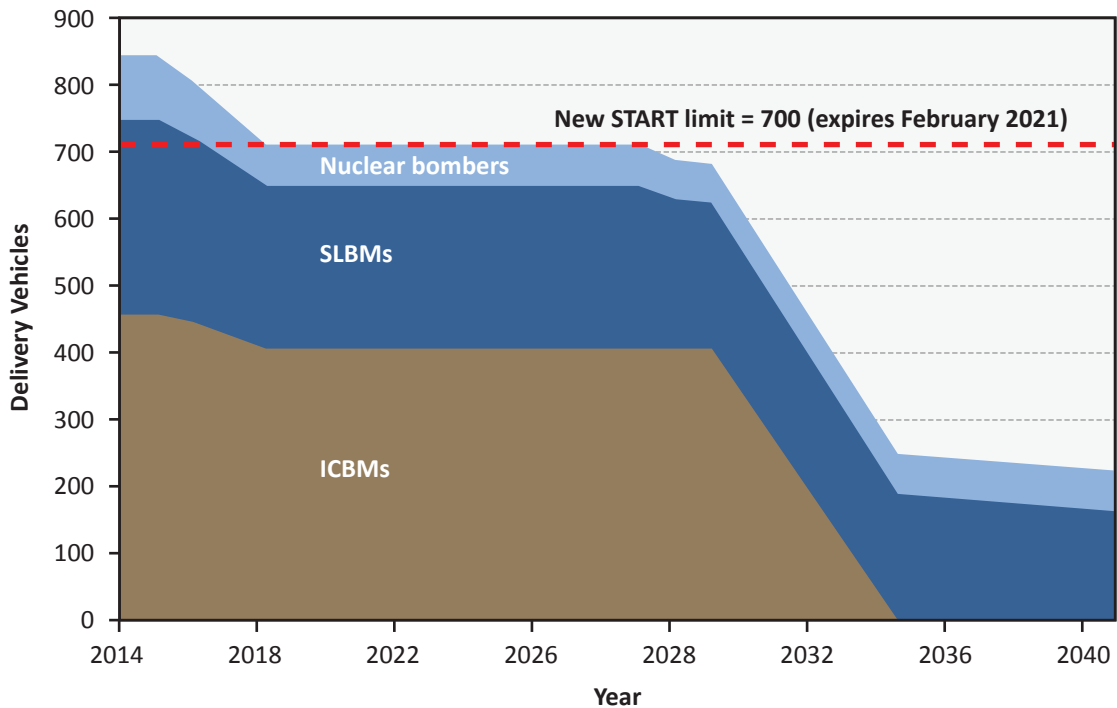


Figure S-1. US Strategic Delivery Vehicles with the Fiscal Year 2015 Program of Record

We learned that triads perform better than bomber-SSBN dyads of similar cost in terms of the number of surviving US weapons if the US forces are in a day-to-day posture at the time of an enemy attack. Under most conditions, SSBNs at sea are highly survivable. By contrast, SSBNs in port are highly vulnerable, and that is also true for bombers on the ground, unless they are on a high state of alert. To reduce their vulnerability, both SSBNs and bombers would have to significantly increase their day-to-day alert posture. Even if they did, triads perform better than dyads in terms of the price to attack imposed on the enemy and the ratio of surviving US weapons to remaining enemy weapons after a large enemy first strike.

We also considered the value of enhancing the survivability of the silo-based ICBMs in the future. We concluded that there would be major benefits to harder silos up to a point. Once threat systems advance in accuracy to a circular error probable (CEP) of less than 150 feet, the benefits decline rapidly. The decision to invest in increased survivability through harder silos should be traded against the estimated time it will take our potential enemies to reach a CEP of less than 150 feet. Even if we do not increase the ICBM survivability, an ICBM force will still be survivable against a weak attack and will drive up the price to attack for enemies with significant nuclear capabilities, making a triad the most desirable choice for the future.

Recent US policy, as of December 2016, had a long-term goal of “a world without nuclear weapons,” but for the foreseeable future it recognized the imperative of maintaining a “safe, secure, and effective” arsenal as long as nuclear weapons exist.¹ To provide these capabilities, the United States has relied on a triad of intercontinental ballistic missiles (ICBMs), submarine-launched ballistic missiles (SLBMs) on ballistic missile submarines (SSBNs), and long-range nuclear-capable bombers since the early 1960s. Most recently, the 2010 *Nuclear Posture Review* endorsed this triad force construct through the early 2020s at least.² However, the *Nuclear Posture Review* did not address nuclear forces beyond about 2025, and there is a wide range of opinions on the size and composition of US nuclear forces necessary for the middle of the twenty-first century.

This nuclear triad has played a key role in US security for decades, but most current nuclear delivery systems—the B-52 bomber, the AGM-86 air-launched cruise missile (ALCM) for the B-52, the Minuteman III ICBM, the *Ohio*-class SSBNs, and the Trident D5 SLBM—will reach the ends of their lives between the late 2020s and, perhaps, 2050.

Motivated by the end-of-life issues just described, this report provides analyses relevant to major policy and acquisition decisions in the nuclear mission area, such as whether to maintain a triad or move instead to a dyad and whether current nuclear capabilities are sufficient. The discussion in this report is organized as follows:

- Current nuclear forces and associated nuclear recapitalization issues
- Analysis of key metrics for nuclear forces

¹ Speech by President Obama in Prague, 2009, <https://www.whitehouse.gov/the-press-office/remarks-president-barack-obama-prague-delivered>.

² *Nuclear Posture Review Report* (Washington, DC: US Department of Defense, February 21, 2010).

- Survivability of future US ICBMs
- Survivability of SSBNs and bombers against a preemptive counterforce attack and survivability of SSBNs at sea
- Target coverage for ICBMs, SLBMs, and cruise missiles
- Analysis of candidate force structure options
- Conclusions and observations

The appendix discusses various technical issues pertaining to ICBM survivability.

Before proceeding, we note a few caveats. This study examines the survivability of US nuclear forces after an enemy strikes first in a counterforce attack, analyzing US forces in both a generated posture (maximum alert) and a day-to-day posture (normal peacetime operations). This study does not attempt to assess the likelihood of an enemy preemptively attacking US nuclear forces, nor does it attempt to assess the most likely US alert posture at the time of such a preemptive attack. Furthermore, an attack while US nuclear forces are in a day-to-day posture does not automatically equate to a “bolt out of the blue” with no preceding crisis. Finally, modeling efforts described in this report rely on several assumptions:

- American and Russian forces will comply with the limits in the New START Treaty, even after New START expires.
- In US forces that have new silo-based ICBMs, those ICBMs are allowed to carry multiple warheads per missile to the extent compatible with New START limits. This is contrary to current US policy, but Russia currently shows no indication of limiting its ICBMs to one warhead per missile (and is not likely to do so in the future), and this study assumes that the United States might respond in kind.
- For modeling the survivability of current ICBM silos, this report assigns a uniform hardness value

to all US silos. The actual hardness may vary slightly from silo to silo.

- If the United States has a mixture of single-warhead and multiple-warhead ICBMs, then single-warhead and multiple-warhead missiles will be equally likely to survive a preemptive attack.

Current Nuclear Forces and Recapitalization Issues

The triad includes 14 *Ohio*-class SSBNs, of which 12 SSBNs are normally operational. Each SSBN has 24 Trident D5 SLBMs, although this number will drop to 20 by 2018 in compliance with New START limits. The *Ohio* Replacement Program, which has been under way for several years, is planned to deliver 12 new SSBNs, each with 16 SLBMs. The planned procurement profile consists of one ship in 2021, one ship in 2024, and one ship per year from 2026 until the last ship is procured.³

There are also 96 nuclear-capable bombers (76 B-52s and 20 B-2s). Under New START, the number of nuclear-capable bombers will be cut to 60 when some B-52s are modified so that they cannot carry nuclear weapons. The B-52 relies entirely on the ALCM, whereas the B-2 currently relies on unguided bombs. A new stealthy bomber, the B-21, has been under development for several years, but the Air Force has not announced the initial operational capability date for this aircraft. The B-21 will be nuclear capable, although the Air Force has not announced how many nuclear weapons it will be able to carry or when nuclear initial operational capability will occur relative to conventional initial operational capability. The Air Force is also developing two nuclear weapons for aircraft: the long-range standoff (LRSO) cruise missile to replace the ALCM and the B61-12 guided

bomb. The new bomb will be used by stealthy bombers and the F-35A. The LRSO is planned for use by bombers only, although external carriage by the F-35A might be feasible (but with arms-control implications).

Today's ICBM force consists of 450 Minuteman III ICBMs deployed in silos built between 1962 and 1967. This number is down from a Cold War peak of 1,054 ICBMs. Under the New START Treaty, the United States plans to reduce the number of its operational ICBMs to 400. All 450 silos and all launch control centers may be retained to maintain an option to deploy 450 ICBMs in the future. Although the Minuteman III initially carried three warheads per missile, each missile now carries only one reentry vehicle.

The long-term future of the ICBM force represents a major recapitalization decision. Abandoning the ICBM force will require a major shift in long-standing policy, whereas having an ICBM force in 2050 will require a major infusion of funds (anywhere from \$15 billion to more than \$100 billion, depending on the approach). The budget for fiscal year 2016 includes \$75 million to begin work on a future ICBM, but no details have been released yet on missile characteristics (for example, range, payload, and accuracy), basing mode, or the planned size of the ICBM force. Moreover, with an end of life for current ICBMs at around 2030 and considering the typical development time lines for large missiles, it may be difficult to avoid dropping below 400 ICBMs even if the long-term goal is to have a force of 400 ICBMs or more. Finally, funding requirements for this program may exceed \$1 billion per year for a significant number of years, starting in the early 2020s, and the new ICBM will have to compete for funding with the F-35 fighter, the B-21 bomber, the KC-46 tanker, the T-X trainer, and (possibly) various big-ticket items in the Navy and/or Army. Hence, providing full funding for the new ICBM may be challenging, absent an increase in the defense budget, and discussions about

³ It will also be necessary to start an SLBM program within the next five to seven years to maintain SLBM availability into the 2050s and beyond.

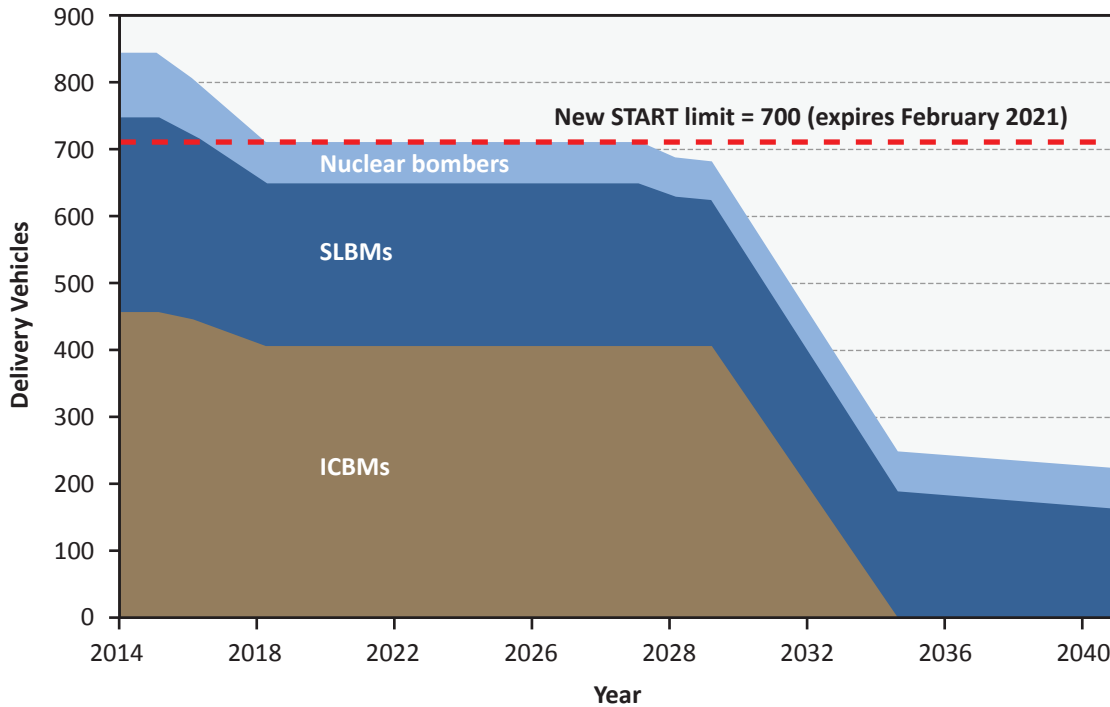


Figure 1. Current and Future Delivery Vehicles under the Fiscal Year 2015 Program of Record

the need for ICBMs may take place in the nuclear posture review.

Although this report addresses a variety of topics, the two most important questions it considers are the following:

- (1) Should the United States retain an ICBM force beyond the end of life currently projected for Minuteman III (probably around 2030)?
- (2) If so, what characteristics should the future ICBM force have?

In addressing these questions, we assume that any future ICBM force would almost certainly be deployed in addition to SSBNs and bombers.⁴ Also,

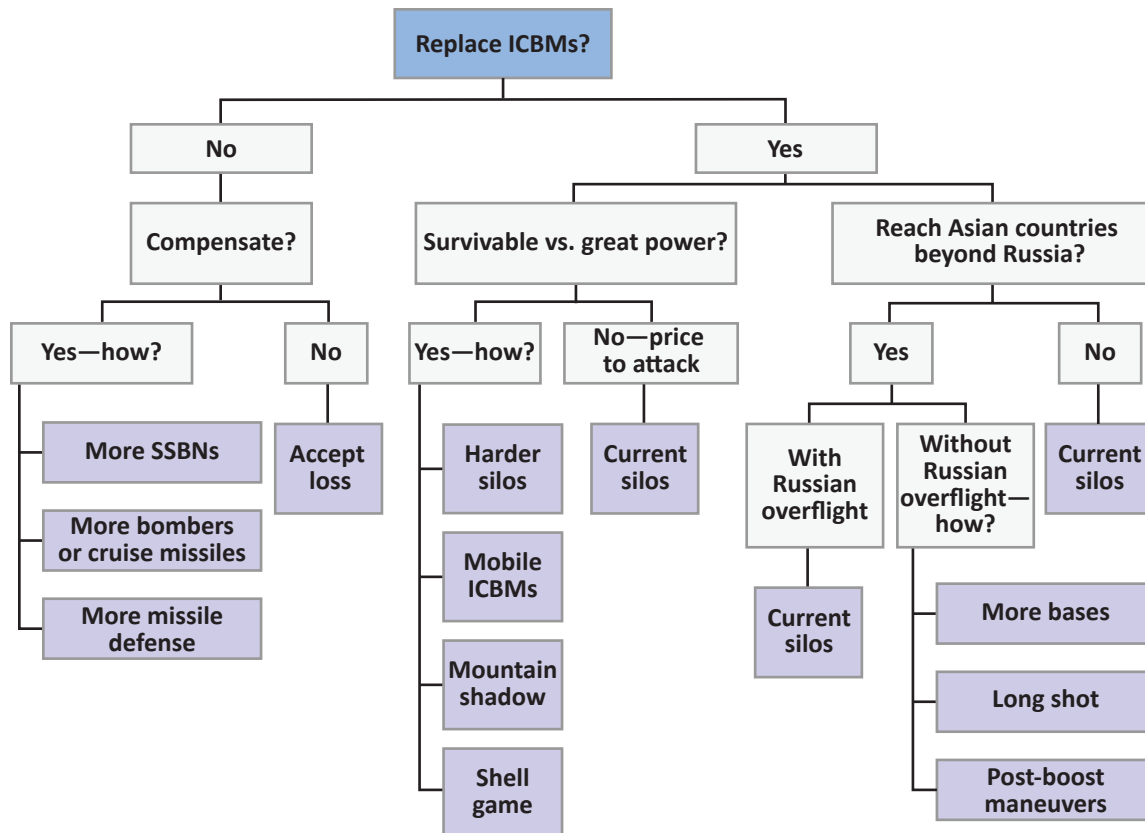
⁴ Numerous studies over the last 20 years have indicated a strong need for bombers in conventional war, and the B-21 program has been under way for several years. Moreover, the cost increment to make a bomber nuclear capable (if nuclear capability is “designed in” from the beginning) is small, so nuclear bombers are likely to be retained. The only scenario where it might make sense for the bomber force to be “conventional only” would be one where counting rules in a future nuclear arms-control treaty are unfavorable to bombers. Arguments based on survivability make

we recognize that the two questions are not easily separated. For example, a decision to build a new ICBM might be contingent on having that future system provide important advantages over the current force. Our goal is not to answer these questions, but rather to identify issues that should be considered and provide relevant information to help inform decisions on nuclear policy, acquisition efforts, and force structure.

To highlight the impact of decisions on the future of the ICBM force, Figure 1 shows that the number of US nuclear delivery vehicles will decline from 834 in 2015 to about 220 by 2040 with the fiscal year 2015 program of record, which did not include ICBM recapitalization.⁵

it very unlikely that SSBNs will be eliminated. Hence, this study did not consider any dyads other than bomber–SSBN dyads.

⁵ The figure accounts for the delivery schedule for the future SSBN, the retirement schedule for the *Ohio*-class SSBNs, the number of tubes per *Ohio*-class SSBN and per future SSBN, and the estimated “die-off” schedule for the Minuteman III. Declines before 2020 are driven by New START compliance. Declines starting around 2030 are driven mainly by Minuteman III end of



If the United States has a large ICBM force based in silos that are not very survivable, US ICBMs might not contribute much to the number of surviving US warheads after a large and accurate preemptive strike, but these silos could greatly drive up an enemy's price to attack and could positively influence the US–enemy weapon balance after the first strike.

Figure 2. Decision Tree for Future ICBMs

Figure 2 shows a decision tree for the future of the ICBM force. The overarching decision, of course, is whether to keep ICBMs beyond about 2035. If the answer is no, then the next question is whether to compensate by increasing something else beyond the program of record or live with the program of record for bombers and SSBNs. This report considers options for living with the program of record and for making the SSBN force more robust. Some analyses for compensation measures that do not involve SSBNs

life, with a secondary factor being the difference in the number of SLBM tubes between an *Ohio*-class SSBN and a future SSBN. The figure assumes that the number of nuclear bombers will stay at the New START level of 60, although it would be possible to increase the number of nuclear bombers in the 2030s, even if the ICBM force stays at 400 missiles, without violating the New START limits on delivery vehicles.

(an expanded nuclear bomber force and nuclear cruise missiles on attack submarines) are in progress.

If the nation decides to retain ICBMs in the 2040s and beyond, two key questions arise:

- (1) **How survivable will future ICBMs need to be against a large and advanced attack?** This is discussed in the next section, along with various options for improving ICBM survivability.
- (2) **Will future ICBMs need to reach Asian targets more distant than Russia, especially without flying over Russia?** Techniques for achieving such a capability are discussed in a later section.

Before moving on to the modeling that we did, we discuss several factors that influence the type of nuclear forces that the United States might need in

the future, and how these factors relate to ICBMs. These factors include the following:

- **Security context:** When the United States first deployed ICBMs in the current silos in the 1960s, the Soviet Union was the only adversary of interest. ICBMs were well suited to reaching the Soviet Union on transpolar trajectories, and the silos were highly survivable because of the poor accuracy of early Soviet missiles. In the future, the survivability of silo-based ICBMs may decline due to improvements in the accuracy of foreign nuclear weapons. Moreover, the number of potential adversaries may grow to four or more, and ICBMs based in the United States cannot reach much of Asia without flying over Russia. On the other hand, it is unlikely that the United States will face any adversary with a nuclear arsenal on the scale of what the Soviet Union once possessed.
- **Budgetary constraints:** Future ICBMs will have to compete for funding with the F-35 fighter, the B-21 bomber, the KC-46 tanker, the T-X trainer, and, possibly, programs outside the Air Force. Hence, it may be hard to provide full funding for ICBMs in the 2020s, and this factor stresses the importance of finding an affordable, possibly incremental, approach to ICBM recapitalization.
- **Risks in other strategic programs:** Without ICBMs and/or major improvements in bomber survivability against a preemptive attack, US forces would be vulnerable to unexpected improvements in foreign antisubmarine warfare and to a small preemptive counterforce attack. Moreover, there is still significant technical and schedule risk in the programs for the B-21 and the new SSBN, and there could be unexpected issues with the service life of the Trident D5 or the current SSBNs. Taken together, these factors emphasize the importance of ICBMs.
- **Desirable attributes for US strategic forces:** Survivability against a preemptive attack, target coverage, and the price to attack imposed on an

enemy are discussed in this report. Other desirable attributes include endurance of US forces after an attack, lethality, the ability to achieve acceptable lethality while minimizing collateral damage, speed of response, and in-flight survivability. Without ICBMs, the US nuclear deterrent force would probably have poor long-term endurance after even a small preemptive counterforce attack because the bomber bases, SSBN bases, and all nuclear weapons storage sites would be destroyed. By contrast, surviving ICBMs that were not used in the immediate retaliatory strike would probably be available for use over a long period of time. Lethality and collateral damage depend on accuracy and explosive yield, and it is possible to achieve a desirable yield–accuracy combination in an ICBM, an SLBM, a guided bomb, or a cruise missile. Similarly, speed of response and in-flight survivability favor ICBMs and SLBMs over other delivery systems but are not very helpful for comparing ICBMs and SLBMs.

Survivability of Future US ICBMs

If the United States decides to retain ICBMs after Minuteman III reaches the end of its life, then it will be necessary to decide how survivable the future ICBM needs to be. Moreover, information on how survivable a future ICBM *could* be might be a key factor in deciding whether to recapitalize ICBMs. For example, a decision to retain ICBMs into the 2040s and beyond might be contingent on improving their survivability. Five main variants for a future ICBM force structure may be worth considering in a cost–benefit analysis for survivability and price to attack:

- (1) ICBMs in the current silos
- (2) ICBMs in new, harder silos on the current bases
- (3) Mobile ICBMs on the current bases
- (4) Silo-based ICBMs at new locations that provide terrain masking against ballistic missile attacks
- (5) Shell-game ICBMs on the current bases

Attacks against a Single ICBM Silo

We begin with the survivability of a single ICBM silo against a single warhead and then proceed to force-level considerations. The survivability of an ICBM silo against an incoming warhead depends on the following factors, along with the reliability of the enemy weapon system:

- (1) Accuracy of the incoming warhead (most important)
- (2a) Hardness of the ICBM silo (tied for second-most important)
- (2b) Explosive yield of the incoming warhead (tied for second-most important)

Because more detailed information is classified, only a parametric treatment is possible in this report. The appendix explains the mathematical background for survivability and contains several curves that illustrate the impact of target hardness, weapon yield, and accuracy on single-shot kill probability against a hard point target such as an ICBM silo. The appendix shows a strong relationship between target survivability and target hardness if the accuracy of the nuclear weapon

(as measured by circular error probable, or CEP) is at least 200 feet but a weaker correlation once the CEP gets below 200 feet. Survivability is invariably poor in the limit of extremely good CEP (such as 150 feet or less), at least for yields in the hundreds of kilotons. In other words, making silos harder may be a viable way to improve ICBM survivability if the CEP of missiles attacking those silos exceeds 150 feet.

Attacks against a Force of Silo-Based ICBMs

We now consider synergies between silo hardness and force size. Figure 3 illustrates an attack using 800 nuclear reentry vehicles against a force of silo-based ICBMs that is parametrically varied in size from 100 to 800 silos. In the real world, a large nuclear attack might involve several types of missile-reentry vehicle combinations, with sizable variations in yield, accuracy, and reliability. Figure 3 handles this complexity in a simplified, notional way by assuming that the attack consists of 200 highly lethal reentry vehicles, each of which has a 75 percent single-shot kill probability, and 600 less lethal reentry

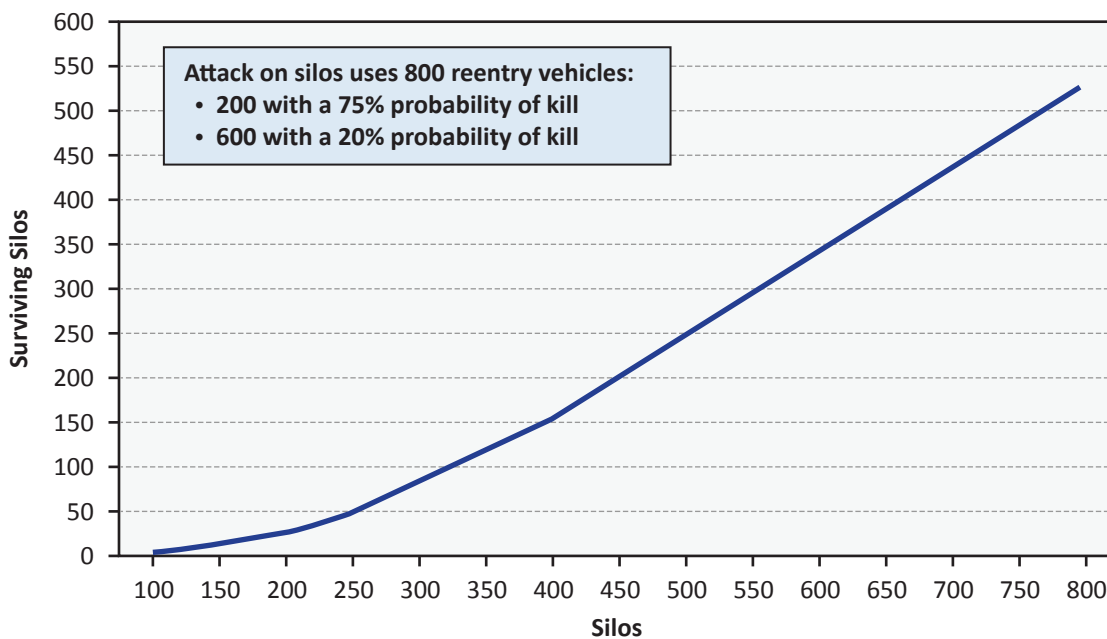


Figure 3. Number of Surviving Silos as a Function of the Number of Silos for an Attack Involving 800 Nuclear Reentry Vehicles of Two Types

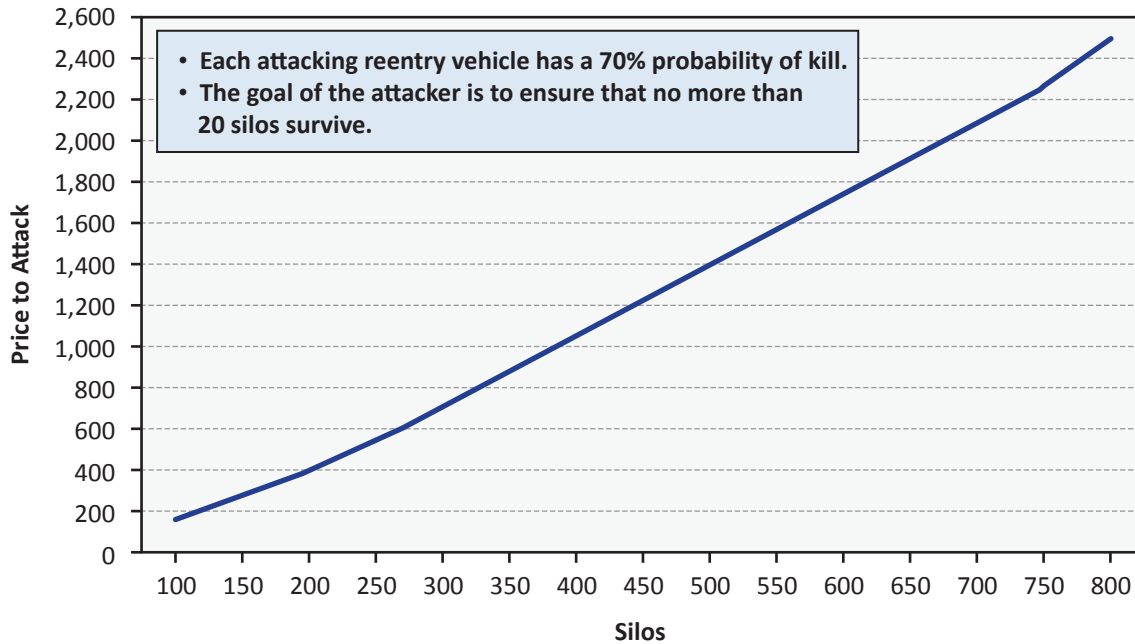


Figure 4. Price to Attack as a Function of the Number of Silos

vehicles, each of which has a 20 percent single-shot kill probability. Figure 3 shows that the number of surviving silos increases from one or two in the force with 100 silos to 530 in the force with 800 silos. In other words, the ability of silo-based ICBMs to contribute to the survivable retaliatory force increases much more quickly than linearly relative to the size of the ICBM force.

Similarly, the number of reentry vehicles needed to neutralize a force of silo-based ICBMs to a desired level would often increase quickly, rather than linearly, relative to the number of ICBM silos. Suppose that an attacker wants to be sure that no more than 20 ICBM silos survive the attack, independent of the number of ICBM silos being attacked. Suppose further that each attacking reentry vehicle has a 70 percent single-shot kill probability. Figure 4 shows the price to attack, as a function of the size of the ICBM force, for destroying all but 20 of the ICBM silos. The number of ICBM silos is parametrically varied from 100 to 800. Increasing the number of ICBM silos from 100 to 800 increases the price to attack by a factor of 17. If the first 200 to 400 attacking reentry vehicles had a high single-shot kill probability and all subsequent

reentry vehicles had a much lower single-shot kill probability, then the price to attack would grow even more quickly than indicated in Figure 4.

Mobile ICBMs

The United States has never deployed mobile ICBMs, although the Air Force did fund prototype mobile ICBMs in the late 1980s. By contrast, Russia and China have had mobile ICBMs for a number of years, and North Korea is beginning to field a mobile ICBM. When considering mobile ICBMs, there is a tension between desirable range-payload characteristics for the missile and desirable mobility and hardness levels for the launcher vehicle. Figure 5 shows the widely fielded Russian SS-25 and a US MGM-134 Midgetman prototype mobile ICBM from about 1990.

The SS-25 is a much larger missile (more payload), whereas the Midgetman vehicle almost certainly would have been more mobile and more damage resistant than the top-heavy SS-25 vehicle. The next two sections discuss the survivability of mobile ICBMs that are operationally deployed in the field



Figure 5. Russian SS-25 (Top) and US MGM-134 Mobile ICBMs (Bottom)

(at the current ICBM bases) and the survivability of mobile ICBMs deploying from garrison under attack.

Mobile ICBMs Deployed outside of Their Garrison

The key question is whether the enemy can detect and track the US ICBMs in real time. If the enemy could do this, which is unlikely, then the mobile ICBMs would almost certainly have poor survivability because they are soft targets that would be vulnerable to accurate nuclear weapons. If the enemy cannot target individual mobile ICBMs, the key survivability issues include the following:

- The size of the operating area available to the mobile ICBMs
- The number and yield of the enemy reentry vehicles

- Russia declared a force of 1,428 reentry vehicles on ballistic missiles under New START, and it would almost certainly be impossible to use 90 percent or more of these reentry vehicles to attack US ICBMs.
- Accuracy would not be a major factor if the lethal radius of each enemy warhead were several times greater than the CEP.
- The hardness of the mobile ICBMs
 - A 2014 RAND report, *The Future of the U.S. Intercontinental Ballistic Missile Force*,⁶ attributed hardness values of 15 to 30 pounds per square inch to mobile ICBMs. For purposes of analysis, this report will use the RAND hardness values without attempting to verify their accuracy.

The combined area of the three US ICBM bases is on the rough order of 80,000 square kilometers, of which possibly 80 percent might be usable. Depending on weapon yield (assumed here to be in the 100- to 500-kiloton range) and the hardness of the ICBM launcher vehicles, an individual nuclear warhead might have a lethal area of about 2 to 8 square kilometers. This suggests that a barrage attack against ICBMs deployed in the field would require at least 10,000 warheads, and possibly several tens of thousands. In other words, a barrage attack against deployed mobile ICBMs is infeasible if the ICBMs take full advantage of the land area at the current bases. See the appendix for more details.

Mobile ICBMs Deploying from a Garrison under Attack

The discussion above is appropriate to a situation in which the US ICBM force is on its maximum state of alert. In a day-to-day posture, however, a majority of the mobile ICBMs might be indoors

⁶ Lauren Caston et al., *The Future of the U.S. Intercontinental Ballistic Missile Force* (Santa Monica, CA: RAND Corporation, February 2014).

in garrisons. The survivability of mobile ICBMs deploying from garrison under attack depends on the following factors:⁷

- The number and yield of the incoming warheads
- The number of US garrisons
- The hardness of the vehicles carrying the mobile ICBMs
- The speed with which the ICBMs can get away from the garrison (considering how long it takes to receive an alarm, how long it takes the vehicles to get out of the garrison once an alarm sounds, and the top speed of the vehicles)
- Whether each garrison is surrounded by a spoke-like road geometry that allows mobile ICBMs to deploy in many directions at once
- Whether the ICBM vehicles have any off-road capability

If the mobile ICBMs can disperse in every direction from the garrison, which would likely require that the mobile ICBMs be able to travel off road (and which might reduce the speed of the mobile ICBMs), then the enemy would be faced with conducting barrage attacks of limited areas around each US garrison. With the same assumptions about the lethal area associated with each enemy reentry vehicle, and with assumed lower and upper limits of 15 and 45 US garrisons, then the number of enemy reentry vehicles required to saturate the areas around the garrisons could be anywhere from 120—which would be easy for a great nuclear power like Russia—to more than 10,000—a number that far exceeds the assessed number of Russian nuclear warheads that can reach the United States. In other words, the compounded uncertainties from a large number of variables with poorly understood values makes it impossible to

reach any reliable conclusions about the survivability of mobile ICBMs deploying in every direction from a garrison. See the appendix for more details.

If the US mobile ICBMs are road based, then the enemy is faced with a linear problem. The number of miles of road that the enemy would need to saturate would depend on the speed of the US mobile ICBMs (which would likely be considerably greater than for mobile ICBMs traveling off road) and the road geometry around each garrison. For example, if there were a dozen spokes leading away from a garrison in multiple directions, this would make more miles of road accessible than would be the case if the only options for an ICBM emerging from the garrison were to go east or west.

With the same assumed limits on the number of US garrisons, plausible assumptions on the speed of the ICBM vehicles, and anywhere from 4 to 12 spokes per garrison, the number of enemy reentry vehicles needed to destroy all of the US ICBMs deploying under attack might range from under 200 to on the order of 9,000. As was the case before, the compounded uncertainties from a large number of variables with poorly understood values makes it impossible to reach any reliable conclusions about the survivability of road-mobile ICBMs deploying from a garrison under attack. See the appendix for more details.

Other Options for Improving ICBM Survivability

Another option—one that has not received much attention lately—is a shell game. The idea is to produce modestly hardened, widely spaced shelters, each of which would contain an erector launcher for an ICBM. The number of these shelters would exceed the maximum number of reentry vehicles available to any adversary, and each shelter would be filled randomly with either a real missile or a decoy. This approach could drive up the price to attack in direct proportion to the number of structures built. The

⁷ This discussion refers to an aboveground garrison of the type that would be likely at the current US ICBM bases. If the garrison were a hard and deeply buried target, it might be able to ride out an attack.

key question for this option is whether the enemy could determine which structures contain the real ICBMs. If the enemy could do this (which might be facilitated by on-site inspections associated with arms control), then the survivability of the US force would be poor and the enemy's price to attack might be lower than for attacking a similar number of much harder ICBM silos. Moreover, this option would be infeasible under the New START Treaty because each structure would count against the limit for delivery vehicles. Consequently, this option will not be examined further.

A final option—yet to be fully analyzed—would be to shift some basing from the plains to mountainous regions. If these missile silos were built in the geometric shadow on the southern side of high or steep mountains, then enemy reentry vehicles approaching from the north would be forced to maneuver violently in the endgame while at the same time maintaining very high accuracy. Or, as an alternative, the adversary could rely more heavily on SLBMs, but the SSBNs would have to launch these missiles from southern waters to reach the US silos using ballistic trajectories. Both of these approaches could force asymmetric burdens on adversaries:

- If the new ICBM silos were at the maximum practical level of hardness, this would drive an enemy requirement for improved accuracy, whereas the violent endgame maneuver to avoid hitting the mountain (for a reentry vehicle approaching from the north) could degrade accuracy.
- A maneuvering reentry vehicle would be larger than a ballistic reentry vehicle with the same warhead, and this could reduce the number of reentry vehicles per missile.
- Depending on the locations of foreign SSBN bases, the number of adversary SSBNs on patrol in tropical launch areas could be low.

Absent a major force reduction, political considerations argue against closing any of the current

bases, so the most likely way to implement this idea would be to build a few dozen new silos on land that DoD or the Department of Energy already owns, while retaining the current bases. Key questions on this approach are (1) how many suitably shielded locations exist for new silos, and (2) whether the same mountain can shield a silo against enemy missiles coming from a realistic variety of launch points. Further analyses on this topic may be warranted.

Section Summary

General conclusions about ICBM survivability are as follows:

- There might be major benefits to harder silos when the CEP of the attacking weapons exceeds about 150 feet, but these benefits decline rapidly for CEPs of 150 feet or smaller.
- It is uncertain whether harder silos can compensate for major reductions in the number of silos.
- The benefits of silo-based ICBMs increase rapidly as the size of the ICBM force grows, both in terms of adding to the survivable retaliatory force and also in terms of driving up the enemy's price to attack.
- Mobile ICBMs deployed in the field before an enemy attack should be highly survivable unless the enemy can detect and track individual mobile ICBMs in real time. Such a capability is not very likely.
- It is hard to assess the survivability of mobile ICBMs deploying from garrison under attack, due to the compounding effects of uncertainties in numerous relevant parameters.
- Use of mountains to mask silos at a new ICBM base could be beneficial to survivability, but implementing any such idea would be expensive and might face severe political problems.

Considerations for a Bomber–SSBN Dyad

When considering a bomber–SSBN dyad, the most important factors may be survivability of SSBNs and survivability of bombers against a preemptive counterforce attack. Possible improvements to the forces should also be analyzed.

Survivability of SSBNs

Under most conditions, and if operated intelligently, SSBNs at sea are probably highly survivable. By contrast, SSBNs in port are highly vulnerable to a small nuclear attack. SSBNs at dock are also vulnerable to attacks from conventional antiship cruise missiles launched from attack submarines or bombers. Improved missile defenses, possibly including terminal ballistic missile defense or cruise missile defense at the bases, might reduce vulnerability to a conventional attack or a small nuclear attack. Missile defense would be unlikely to make the SSBN bases survivable against a large nuclear attack.

Survivability of Bombers

Meaningful analyses of in-flight survivability for aircraft or cruise missiles cannot be included in an unclassified report. Much like SSBNs in port, bombers that are on the ground and not on alert are extremely vulnerable to even a small preemptive attack. If on maximum nuclear alert, it is likely that most, or perhaps all, US nuclear bombers would get airborne in time to survive. Analyses on this topic are currently in progress. Absent a change in US policy, however, it is unlikely that bombers would be on nuclear alert except in the context of a severe and prolonged crisis.

Ways to Enhance a Bomber–SSBN Dyad

Finally, it may be worthwhile to examine improvements that might be needed for the SSBN and bomber forces to operate more effectively as a dyad.

Possible enhancements that might be needed include the following:

- More than 12 SSBNs, more than 60 operationally deployed nuclear bombers, and/or an increase in the procurement objective for the LRSO next-generation cruise missile
- Cruise-missile defense and/or terminal ballistic missile defense at the SSBN bases and bomber bases to reduce vulnerability to small attacks
- The ability to provide significant support to SSBNs at bases other than Bangor and Kings Bay, in case these bases are damaged
- Improved defenses against terrorist attacks at the SSBN and bomber bases
- Keeping one bomber base on nuclear alert at all times
- Increasing the number of bomber bases and reducing the number of bombers per base, which would have two benefits:
 - It would slightly increase the enemy’s price to attack.
 - The number of bombers that can take off from one base within the flight time of an enemy ICBM or SLBM is approximately fixed (for any specific base layout), and it would be desirable for the number of bombers at a base to be less than or equal to the number that could credibly take off under attack.

In the aggregate, the cost for implementing the enhancements listed above might exceed the cost for maintaining the ICBM force indefinitely.

Target Coverage for ICBMs, SLBMs, and Cruise Missiles

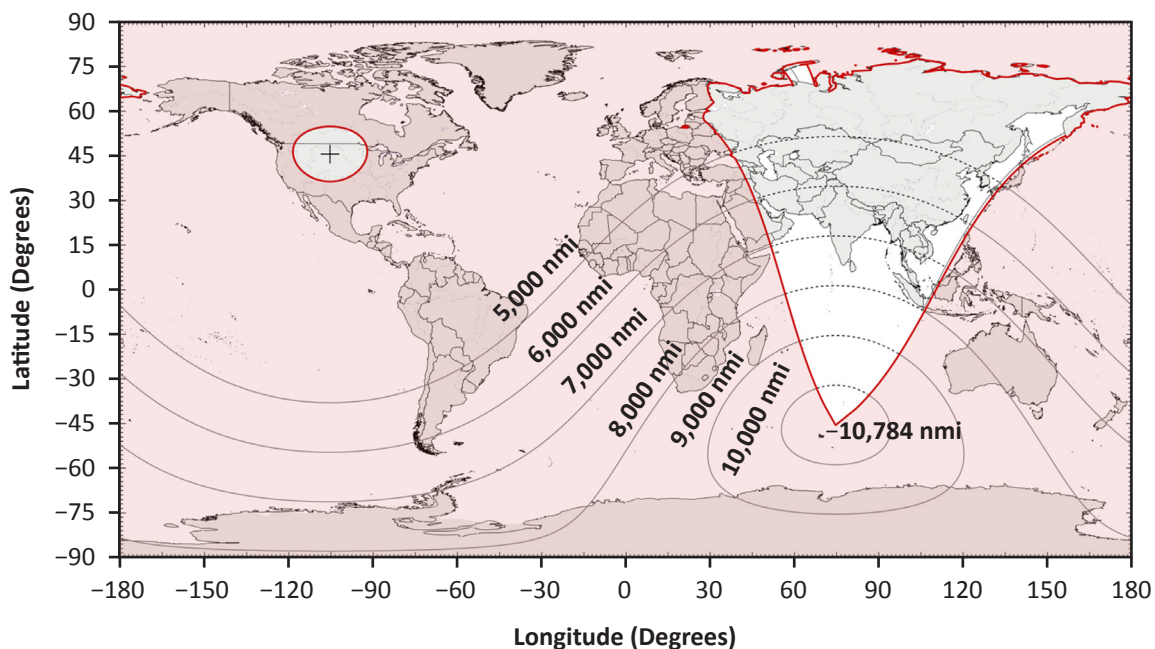
In the 1960s, ICBMs had easy access to the Soviet Union—the only important adversary—and they still do. ICBMs can reach Russia from the current bases

without flying over any country other than Canada. If launched from advantageous locations, SLBMs can also reach Russia without flying over any other nuclear power. In 2040, by contrast to the situation when US ICBMs were initially deployed, there may be several potential adversaries of interest. Figure 6 shows target coverage from the current bases, without overflight of Russia, with a missile range that is parametrically varied from 5,000 to 10,784 nautical miles. From the current bases, today's ballistic missiles cannot reach much of Asia without flying over Russia.

Will future ICBMs have to reach countries other than Russia without flying over Russia? If not, then a medium-sized ballistic missile on the current bases is fine, and other systems would provide all coverage for countries in the "ballistic shadow" of Russia. However, if a future ICBM needs to reach Asian targets without flying over Russia, then major changes are needed to missile characteristics or basing. There are four basic approaches to achieving this capability with ICBMs, none of which is easy. These four approaches are described below. In addition, it is also possible to rely

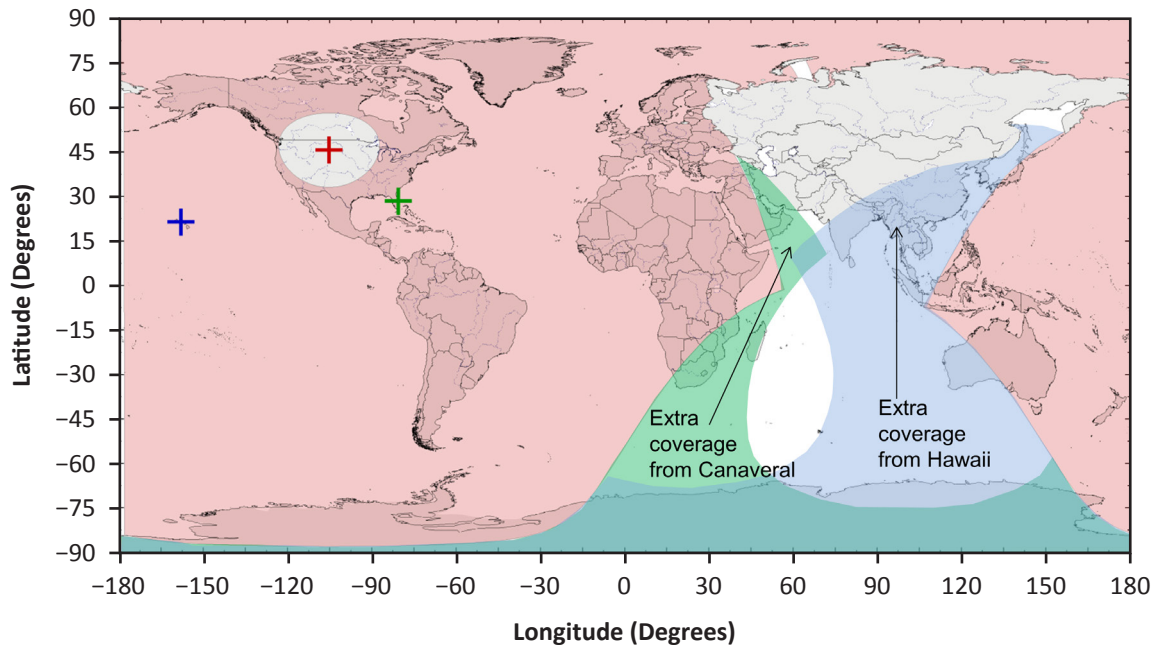
exclusively on SSBNs, cruise missiles, and aircraft for non-Russian scenarios.

- (1) **Using a boost-glide reentry vehicle.** A boost-glide reentry vehicle would fly much of its trajectory in the atmosphere, and it would use aerodynamic maneuvers to go around Russia. A program to develop such a system would entail substantial cost and risk, would require a larger missile to launch a much larger reentry vehicle, and would have aimpoint ambiguity, which could be destabilizing.
- (2) **Using midcourse maneuvers to change directions.** Currently, all ICBM stages provide purely axial thrust with only minor cross axis corrections in the post-boost phase. An extra stage could be added to the missile to direct thrust in a different direction after the "normal" booster stages burn out. Although this approach would not be technically difficult, the resulting missile would be larger than Minuteman III, and aimpoint ambiguity would be an issue.



Reaching regions in white over Asia and the Indian Ocean requires overflight of Russia. Results shown do not include any shadowing due to the small Russian enclaves in Kaliningrad and Crimea. The ellipse in North America bounds the region containing the US bases.

Figure 6. Target Coverage from Current ICBM Bases without Flying over Russia



Reaching regions in white or gray over Asia and the Indian Ocean requires overflight of Russia. Results shown do not include any shadowing due to the small Russian enclaves in Kaliningrad or Crimea. The ellipse in North America bounds the region containing the current bases.

Figure 7. Target Coverage with Extra Bases without Flying over Russia

- (3) **Flying a trajectory over Antarctica from the current bases.** Most targets would be more than 13,000 miles from the US bases. Reaching them would require a much larger missile than Minuteman III.
- (4) **Adding new bases that provide better ballistic access to Asian targets.** Getting out from behind the shadow of Russia requires bases in locations such as Florida, Puerto Rico, Hawaii, or Guam. (Bases near the West Coast would not solve this problem.) Of course, it would not be necessary to base all ICBMs in such locations; most missiles could be in the current bases.

Figure 7 shows the target coverage that would be possible from the current bases, plus a base in southern Florida and a base in Hawaii, for an ICBM with a notional range of 8,000 nautical miles. (Varying the ICBM range parametrically would make the figure too cluttered in this case.) With these bases and this missile range, all of Earth's land area is within range, apart from portions of Antarctica, but significant

portions of Asia are still in the shadow of Russia. Nearly full coverage of the shadowed regions might, however, be possible if the ICBMs at the extra bases in Florida and Hawaii had some sort of maneuvering reentry vehicle, or if the Pacific base was in Guam rather than Hawaii.

Section Summary

It is uncertain whether it is worth pursuing any of the above-described techniques for improving target coverage for ICBMs. Of these approaches, adding two small bases would likely be less expensive and less technically risky than developing a large missile (with large new silos) that could reach non-Russian targets from the current bases without flying over Russia.

Analysis of Candidate Force Structure Options

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) conducted a set of trade-off

analyses between ICBMs and SSBNs in 11 force structure options to shed light on the need for ICBMs and on ICBM–SSBN acquisition decisions. (The number of bombers was held fixed.) These force structures were evaluated against both a large and fairly accurate preemptive counterforce attack and a small preemptive counterforce attack of the sort that a lesser adversary might be able to carry out in 2040 (although such countries probably would not attack US strategic forces).

The enemy attacks occurred under two US readiness postures:

- All US forces on maximum alert; ICBMs ride out the attack
- All US forces in a day-to-day posture; ICBMs ride out the attack

This study did not model use of launch under attack for silo-based ICBMs. This case was omitted for purposes of simplicity and is not an assessment on

the feasibility of launch under attack. (JHU/APL is currently studying launch under attack.) The study assumed that all SSBNs at sea survive and all SSBNs in port are destroyed. The study assumed that all bombers would be destroyed in a day-to-day posture but that most of the bombers would survive if US forces were on maximum alert, without regard for whether a US ICBM force absorbs most of the attacking reentry vehicles. This may not be true. If an adversary could allocate perhaps 1,000 reentry vehicles to an attack against a US bomber–SSBN dyad, then the adversary could conduct a barrage attack on the takeoff zones around the US bomber bases, possibly impairing survivability of bombers on ground alert. The survivability of bombers on ground alert against preemptive attacks of various sizes is currently under investigation.

Table 1 describes the force structure options—four bomber–SSBN dyads and seven triads—that have been studied to date. Future analyses may

Table 1. Force Structure Options Analyzed by JHU/APL

Force Option	ICBMs	SSBNs	Bombers	Accountable vs. Actual Warheads	Delivery Vehicles	Description and Cost (Relative to Option 1)
Bomber–SSBN Dyads						
0	0	10	60	860/1,280	220	See notes below table.
1	0	12	60	1,020/1,440	252	No ICBMs. Cost baseline.
2	0	14	60	1,180/1,600	284	+\$14 billion (B)
3	0	18	60	1,500/1,920	348	+\$42B
Triads						
4	400	12	60	1,420/1,840	652	Minuteman III, current silos and launch control centers. +\$15B
5	510	8	60	1,550/1,970	698	New ICBMs in new, harder silos and new, harder launch control centers. Option 5 = +\$47B Option 6 = +\$56B Option 7 = +\$62B Option 8 = +\$67B Option 9 probably intermediate between options 3 and 4.
6	480	10	60	1,550/1,970	700	
7	400	12	60	1,550/1,970	652	
8	448	12	60	1,550/1,970	700	
9	150	12	60	1,550/1,970	402	
10	448	12	60	1,468/1,888	700	Mobile ICBMs. At least +\$150B.

Costs are approximate and do not include operating costs after the weapons are built.

Force option 1 has a shipbuilding shortfall of about \$36 billion in the 2020s and 2030s to maintain the planned force structure continuously, and this shortfall is also embedded in the other options that have more than 10 SSBNs. We assumed that funding is obtained to eliminate this shortfall. Costs for options 2–10 are measured relative to option 1.

include options with more than 60 nuclear-capable bombers and/or with tactical nuclear weapons that are not currently funded (such as cruise missiles on submarines). The total investment cost for option 1 (research and development, procurement, and military construction) would be about \$180 billion to \$190 billion in 2015 constant dollars, including all development and procurement costs for the B-21, the new SSBN, the B61-12, and the LRSO. Of course, the B-21 is being developed mainly for conventional warfare, and only a small fraction of the total B-21 cost is for the nuclear mission. The investment cost increments for options 2–10, beyond option 1, are included in the rightmost column of Table 1. Options 2 and 4 cost about 7 percent to 8 percent more than option 1. Options 3 and 5–8 cost about 23 percent to 35 percent more than option 1. Option 10 (mobile ICBMs) might cost up to two times as much as option 1 and would likely be cost prohibitive.⁸

In options 5–8, the ICBMs carry a mixture of one and three warheads. In options 4 and 10, each ICBM carries one warhead. In option 9, the ICBMs carry a mixture of one and five warheads.

Two of the force structures in Table 1 include more than 12 SSBNs. These extra SSBNs would not be available until after 2042, unless the United States procured an average of more than one SSBN per year in 2026 through 2035. By contrast, all of the ICBM options could be available by 2035. Additional comments and details on the force structure options include the following:

⁸ Although three categories of dyads are possible, this report includes only bomber-SSBN dyads with variable numbers of SSBNs. The program for the *Columbia*-class SSBN has been under way for years, and there is a general consensus that SSBNs are crucial because of their survivability. The program for the B-21 bomber has been under way for years, there is a consensus that bombers are crucial for conventional war, and the extra cost to make the B-21 nuclear capable is small relative to the overall cost of the program.

- Option 0 could be option 1 before the 11th *Ohio*-replacement SSBN is delivered, or it could be a cheaper option with \$14 billion of savings.
- Option 4 is closer to the planned New START force of 2020 than are any of the other options, but the New START force of 2020 would have more SLBMs than option 4 because of the larger number of tubes per SSBN (20 in 2020 versus 16 in 2045).
- Each SSBN has 16 tubes and a notional 80 warheads. In reality, the fleet would be a mixture of *Ohio*-class SSBNs and 16-tube SSBNs during the 2030s, but it is impossible to predict the distribution between types of SSBNs for the SSBNs at sea in a day-to-day posture.
 - A 16-tube SSBN could carry more than 80 warheads, but high warhead loads reduce the range of the SLBM and the maximum separation between targets that can be attacked. This topic is currently under investigation.
- Each bomber notionally carries eight weapons and counts as one warhead under New START. More refined modeling of bombers would demand use of actual weapon loads for the LRSO cruise missile on the B-2, B-52, and B-21, and B-21 weapon loads for all nuclear weapons.
- In the options with 400 or more ICBMs, new silo-based ICBMs carry either one or three warheads. Minuteman III and the mobile ICBM each carry one reentry vehicle. In the option with 150 new silo-based ICBMs, the ICBM is larger than Minuteman III and can carry up to five warheads.
- All options comply with the New START limits of 700 deployed delivery vehicles and 1,550 deployed warheads. Options 0–2 are well below the New START limit on deployed warheads. Options 0–3 and option 9 are well below the New START limit on deployed delivery vehicles.

We also considered the performance of these US force structure options against a much smaller attack of 50 to 100 reentry vehicles. This is less than the number of US ICBMs in any of the options with ICBMs, so this notional small attack was limited to SSBN bases, bomber bases, and various other non-ICBM targets. Because the ICBMs get a “free ride” in this scenario, the triads uniformly perform better than the dyads, without regard to silo hardness. The triad’s advantages are greatest in a day-to-day posture.

The modeling indicated that, relative to triads of similar cost, bomber–SSBN dyads may perform well in terms of the number of surviving US weapons if the US forces are on maximum alert at the time of a large and accurate nuclear attack. Triads, by contrast, often perform better than dyads of similar cost in terms of the number of surviving US weapons if the US forces are in a day-to-day posture at the time of the enemy attacks. Triads invariably perform better than dyads in terms of the price to attack imposed on the enemy, the ratio of surviving US weapons to remaining

enemy weapons after a large enemy first strike, and survivability against a small nuclear attack. Additional metrics such as target coverage, lethality, collateral damage, and in-flight survivability are important for the nuclear force as a whole but—with the partial exception of target coverage—are not very helpful for choosing between forces when the number of bombers is held constant. In other words, the triad–dyad choice depends on which characteristics are more important to decision-makers, although a triad is better according to most metrics, as shown in Figure 8.

Finally, the option with mobile ICBMs is much more expensive than any of the other options, and it would need to offer compelling advantages to be selected. This option drives a high price to attack on potential adversaries, and it is insensitive to possible future improvements in enemy missile accuracy. However, mobile ICBMs are potentially vulnerable to future improvements in the adversary’s ability to detect and track mobile ICBMs, whereas new and harder silos do not share this vulnerability.

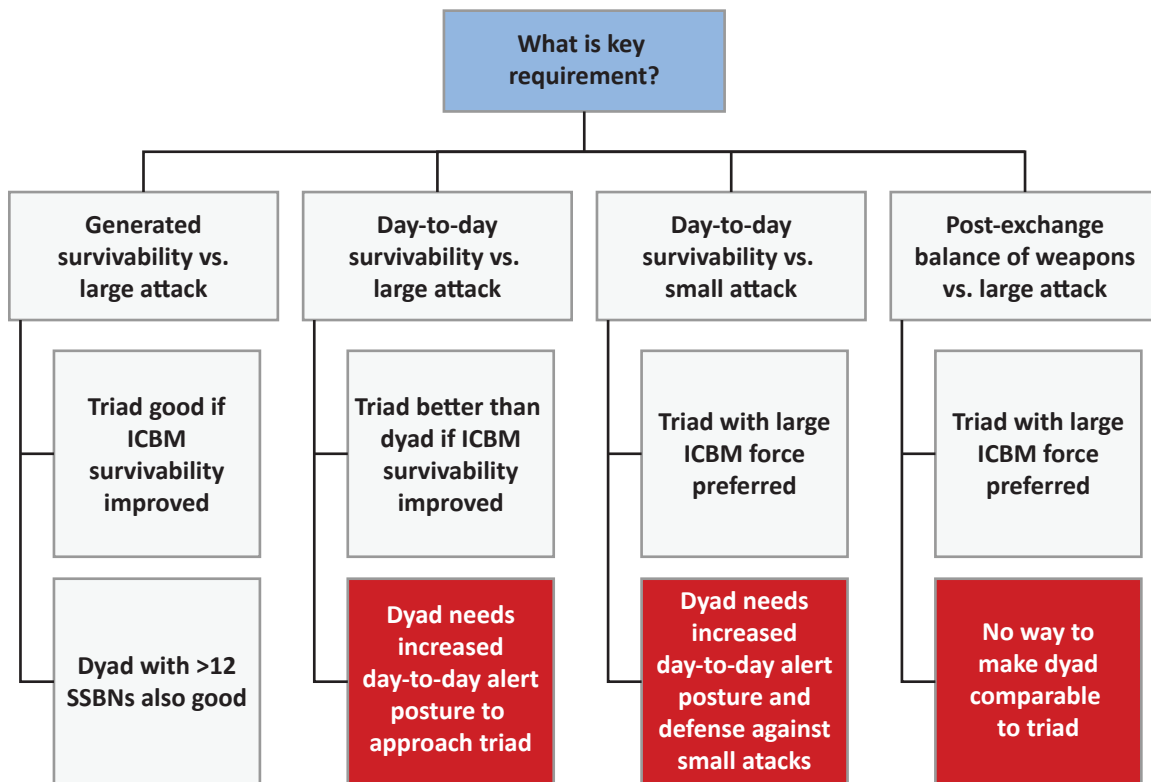


Figure 8. Triad Better Than Bomber–SSBN Dyad on Most Metrics

Conclusions and Observations

The existing ICBM capability is not sustainable beyond the 2030s. Although an ICBM program started in 2016, details are lacking on missile characteristics, force size, and basing. Moreover, the additional cost to retain ICBMs in the 2040s and beyond could be a major burden for the defense budget, especially for the more expensive ICBM options considered.

ICBMs in the current silos were highly survivable in the 1960s because of the poor accuracy of Russian missiles, but US ICBMs may have questionable survivability against a large attack in the 2030s (absent launch on warning), unless the basing mode is changed to harder silos (which could be built after the new ICBMs are procured to reduce annual costs) or mobile ICBMs. Harder silos would improve survivability against enemy missiles in some accuracy regimes, but they are vulnerable to possible improvements in missile CEPs below 150 feet. Mobile ICBMs provide resilience against future improvements in enemy missile accuracy, but they are very expensive and they suffer from potential survivability concerns in a day-to-day posture and are vulnerable to improvements in foreign abilities to detect and track the mobile ICBMs. Even if not very survivable against a large and advanced attack, however, ICBMs can impose a very high cost to attack on a potential adversary. This, in turn, would have a favorable effect on the post-exchange balance of weapons after a large and accurate enemy first strike against US forces. Moreover, ICBMs are intrinsically resistant to small attacks. Thus, in most scenarios, a well-designed triad with a large ICBM force performs better than a dyad and provides more robustness against unexpected problems with one element of the US force or unexpected enemy advances in any one area.

ICBMs at the current bases are useful against Russia and have little role beyond that unless flying over Russia is allowed. Options—all of them expensive—to allow ICBMs to reach Asian targets without flying over Russia include additional bases, maneuvering

reentry vehicles, and a large ICBM that could fire a reentry vehicle on a trajectory over the Southern Hemisphere. Alternatively, it would be possible to accept this limitation and rely exclusively on other systems for use against selected adversaries.

In addition, decisions on future nuclear forces depend on policy questions that physics-based modeling cannot answer, although physics-based modeling can contribute to good decisions on these questions by informing policy makers. Among the most important of these questions are the following:

- **How much is enough?** How many nuclear delivery vehicles and nuclear weapons do we need? What level of threatened retaliation is sufficient to support US deterrence strategy? The number of total US weapons needed depends critically on the survivability of the US force, the number and hardness of targets that need to be destroyed, the lethality and in-flight survivability of the US weapons, and the number of weapons that need to be held in strategic reserve for later use (either in a later strike or for continued deterrence).
- **What role will Russia play in the future?** Future US relations with Russia are critical to determining what US nuclear forces are needed, especially with regard to ICBMs. Will Russia be an adversary for the next 30 years or will relations improve? Might Russia ever be supportive of US overflight in the event of a war between the United States and a country in the ballistic shadow of Russia? Will the Russian economy and demographics allow Russia to remain a great military power? Will Russia continue to invest heavily in nuclear forces?
- **What role will nonstrategic (also known as tactical or theater) nuclear forces play in the future?** Over the course of the last 25 years, the United States has greatly reduced the number and diversity of its nonstrategic nuclear weapons, while Russia has maintained perhaps 2,000 or more such weapons and is modernizing them, with a heavy emphasis on accurate, low-yield weapons.

Russian use of such weapons might negate US/NATO advantages in conventional weapons and/or force the United States into a disproportionate response. JHU/APL is investigating nonstrategic nuclear forces in a separate effort.

- **What role will treaties play in the future?** Most treaties to date have applied only to the United States and Russia (or the Soviet Union) and have been restricted to long-range strategic weapons. Meanwhile, China has become a great military power, could become a great nuclear power, and has a large inventory of weapons that the Intermediate Nuclear Force Treaty bans for the United States and Russia. Should future treaties be trilateral and/or include some types of theater nuclear weapons?
- **How much is the United States willing to invest in nuclear forces?** How much risk are US leaders willing to accept in terms of deterrent capability, the size of the survivable retaliatory force, or the balance of power? How can risk be quantified and presented to US leaders in a manner that facilitates wise decision-making?
- **Do ICBMs need to be survivable against a large and advanced attack?** Or might it be sufficient for ICBMs to be survivable against a weak attack and to drive up the price to attack for an enemy great nuclear power?
- **Is the enemy's price to attack a key factor?** Is it important to drive up the enemy's price to attack to influence the post-exchange balance of weapons, or is it enough to have a large number of survivable weapons?

- **Is the nation willing to consider a bomber-SSBN dyad?** Except in the context of a more benign world, a dyad has serious drawbacks, including increased vulnerability to small nuclear attacks, conventional attacks, and even terrorist attacks.

In conclusion, recent JHU/APL analyses have focused on physics-based modeling, a subset of quantitative analysis that relies on first-principles calculations of things such as survivability, lethality, and the ability to reach targets. Other types of quantitative analyses include mission-level modeling and campaign analysis. In this case, such modeling might include an assessment of the necessary counterattacks against the adversaries that were studied, accounting for approved goals for damage inflicted on the enemy and the required strategic reserve after the US counterattack. Such goals exist, but they are highly classified.

Another type of analysis would evaluate a range of force structures in light of various policy objectives, but current objectives are sufficiently qualitative that any such evaluation might be highly subjective. Physics-based analyses of the nature contained in this report (especially if expanded to include trades involving bombers and/or new theater nuclear weapons) could potentially assist decision-makers to render policy objectives more quantifiable, which in turn could lead to new quantitative analyses and then a further round of clarifying policy goals. In other words, policy evolution and quantitative analyses could be combined in a synergistic, iterative process that would naturally feed into acquisition and force structure decisions, future nuclear posture reviews, and future arms control negotiations.

Appendix Technical Issues Pertaining to ICBM Survivability

This appendix discusses various technical issues pertaining to ICBM survivability and explains the mathematical background for survivability, illustrating the impact of target hardness, weapon yield, and accuracy on single-shot kill probability against a hard point target such as an ICBM silo.

Silo-Based ICBMs

This section contains a technical discussion on the survivability of a single ICBM silo against a single warhead. The relevant factors are the accuracy of the attacking warhead, the hardness of the ICBM silos, the explosive yield of the attacking warhead, and the reliability of the attacking system. For simplicity, we will assume that the attacking system is 100 percent reliable.

We begin with yield. Yield (Y) is a measure of the delivered energy of a warhead. In the case of nuclear warheads, yield comprises thermal energy and a blast wave. The blast wave is a moving shock wave that, upon passing over a location, produces a nearly instantaneous increase in the ambient pressure, called overpressure. This increase in pressure, which produces a crushing force, is then immediately followed by a violent wind resulting in dynamic pressure, which is a pushing force. Any given target may be sensitive to overpressure and/or dynamic pressure, but hardened targets are typically sensitive to peak overpressure. Moreover, the peak overpressure near ground zero is approximately proportional to the inverse of the distance cubed (that is, $P \propto 1/d^3$). Thus, for a given warhead yield, if we double the distance from ground zero (the detonation point), the peak overpressure would be approximately one-eighth of its original value.

For a target at a fixed distance from ground zero, the peak overpressure would increase in an approximately linear manner relative to the yield of the warhead. We can then combine the preceding two proportionalities into a single relation such that $P \propto Y/d^3$. Thus, the peak overpressure at a particular location is considerably more sensitive to the relative location of ground zero than to the warhead yield.

Target hardness is a measure of a target's ability to resist a nuclear blast. Hardened targets, as their name implies, are designed to withstand massive overpressures and dynamic pressures. The ability of a target to withstand a nuclear blast is complex and depends on factors including the construction of the target, warhead yield, blast wave exposure time, and sensitivity to overpressure/dynamic pressure. As mentioned earlier, peak overpressure is typically the damaging mechanism for hardened targets. For our purposes, we assume that target hardness is quantified by the peak overpressure that causes significant damage to the target. We already showed that the overpressure of a nuclear warhead has the approximate form $P \propto Y/d^3$, where Y is the yield and d is the distance from ground zero. If we want to know the lethal radius associated with a target (designated as LR), we need only to equate the hardness (designated as H), to the overpressure relation immediately above such that

$$H = P \propto Y/LR^3.$$

We can rearrange this equation to solve for LR and add a proportionality constant based on empirical data to arrive at the following approximation for LR :

$$LR = 1,600 \text{ feet} * (Y/H)^{1/3},$$

where Y is in kilotons and H is in pounds per square inch.

As an example calculation, consider a 1-megaton warhead and a target with a notional hardness of ~4,000 pounds per square inch. Applying the above equation implies a lethal radius of ~335 meters. The assumption of a lethal radius within which a target is destroyed and outside of which it survives is known as a cookie-cutter distribution. In reality, the target incurs varying degrees of damage depending on its distance from ground zero. Furthermore, a target kill is dependent on the desired level of damage, and the hardness of the target may depend on the orientation of the blast relative to the target. (For an ICBM silo, hardness should be independent of orientation, but the overpressure required to destroy a mobile ICBM might depend greatly on the orientation of the detonation relative to the launcher vehicle.)

Due to a variety of errors, the actual location where a warhead detonates is usually different from the intended location. Henceforth we refer to the intended location (or the point on surface that is directly underneath the intended detonation point for an airburst) as desired ground zero. We can quantify the error in miss distance with the concept of circular error probable (CEP). In Figure A-1, the X indicates our desired ground zero (i.e., the intended location for detonation).

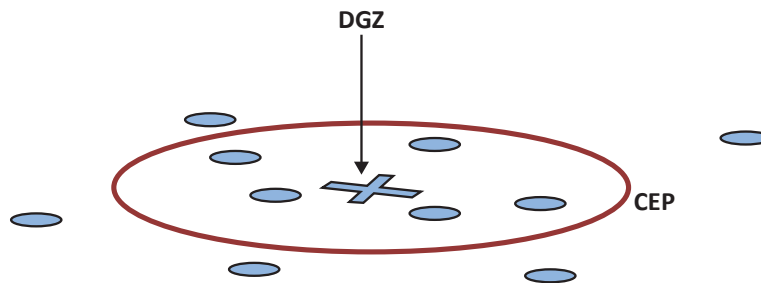


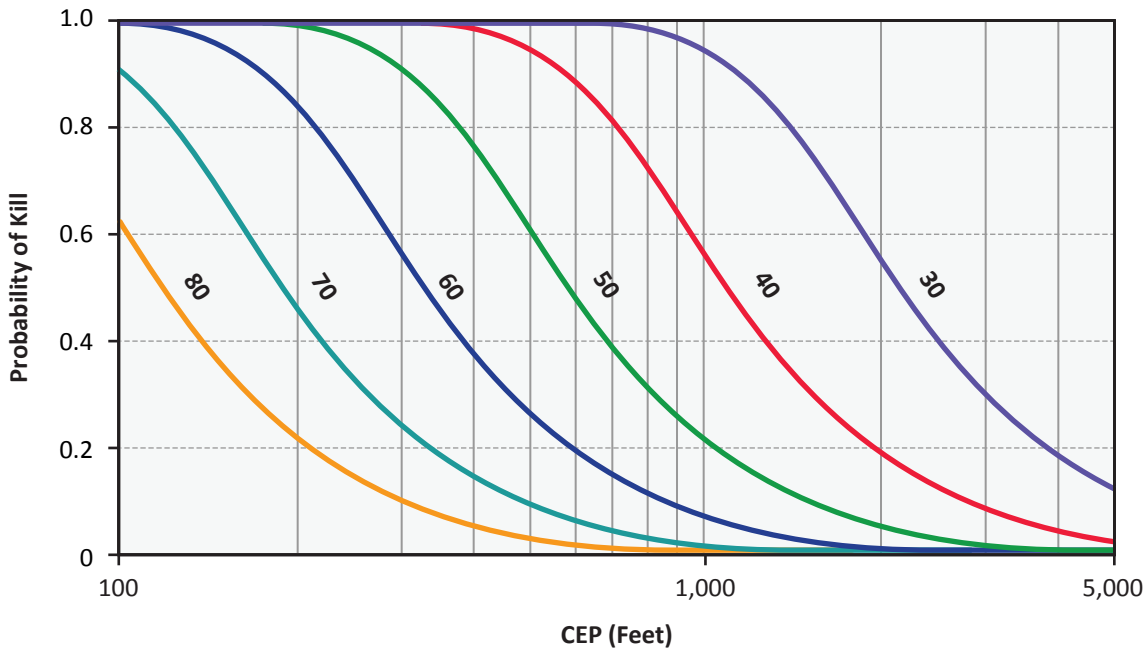
Figure A-1. Desired Ground Zero (DGZ) vs. CEP

The filled circles represent actual detonation locations. CEP is the distance from desired ground zero within which 50 percent of the warheads are expected to detonate. Now, as mentioned earlier, peak overpressure drops dramatically with distance from ground zero and peak overpressure plays a pivotal role in target damage. In addition, the probabilistic nature of CEP introduces a dimension of chance in destroying a target.

Given the inherent uncertainty in the actual ground zero of a warhead relative to the desired ground zero, we can only attempt to calculate the probability of a kill. This value is referred to as the single-shot kill probability (designated by P_k in the formula below):

$$P_k = 1 - 0.5 \frac{1600^2 Y_{kt}^{2/3}}{H_{psi}^{2/3} CEP_{ft}^2}$$

The formula above, in conjunction with the formula for lethal radius, indicates that reducing the CEP of a nuclear weapon by a factor of 2 will have the same impact as increasing the yield by a factor of 8 or reducing the hardness by a factor of 8. However, these effects are dramatic only in the limit where single-shot kill probability is small. The calculations above treat target hardness as a simple pressure value. In reality, the product of overpressure and blast duration is relevant for some targets. In other words, an overpressure of 100 pounds per square inch for 1 second might have the same lethality as an overpressure of 85 pounds per square inch for 2 seconds. VNTK (vulnerability number, complete) is a measure of the hardness of a target against high-yield nuclear weapons (roughly 10 kilotons through several megatons). For most targets, a VNTK value consists of a two-digit number followed by a letter followed by a one-digit number, such as 37Q4. The two-digit VN corresponds to the overpressure needed to damage the target. The required overpressure (for a weapon of a certain reference yield), in pounds per square



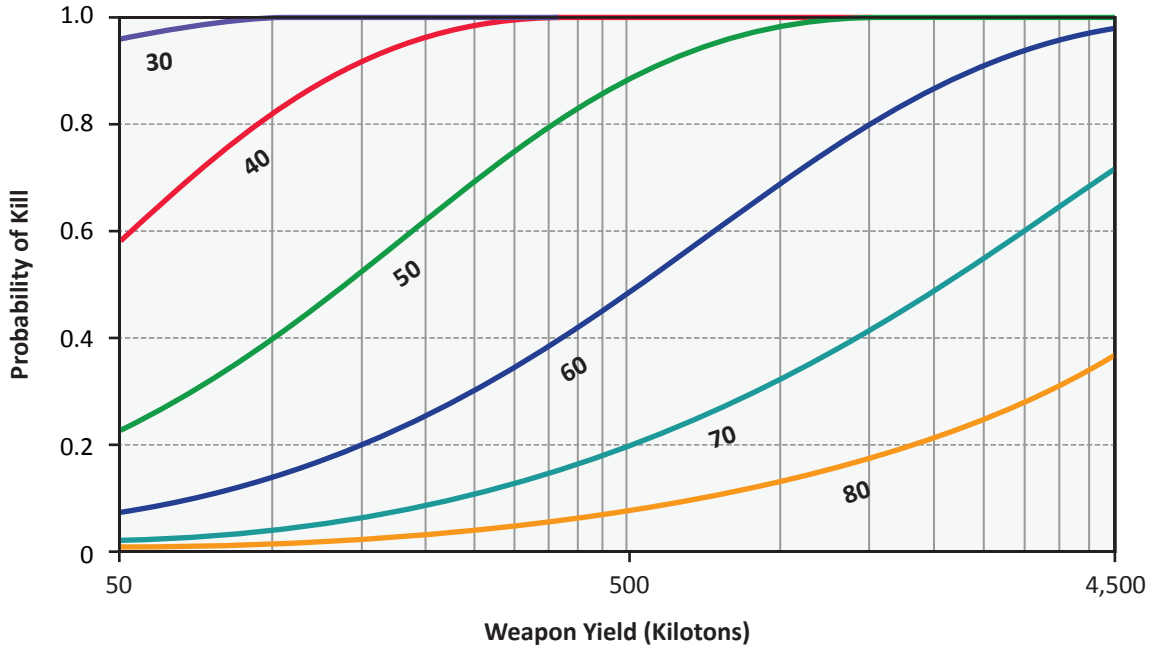
VN values from 80 to 30 in steps of 10, warhead reliability of 100 percent, same warhead yield and TK value for all curves. One curve for each VNTK value.

Figure A-2. Probability of Kill vs. CEP for a Nuclear Warhead against a Hard Point Target

inch, is 1.12×1.2^{VN} . The letter in the VNTK value indicates the primary damage mechanism for the target: peak atmospheric overpressure, average atmospheric overpressure over perhaps a second or two, ground shock, and so on. The final digit indicates the extent of sensitivity to the duration of the blast wave. (The VNTK values for deeply buried targets have a different structure and contain more than four characters.)

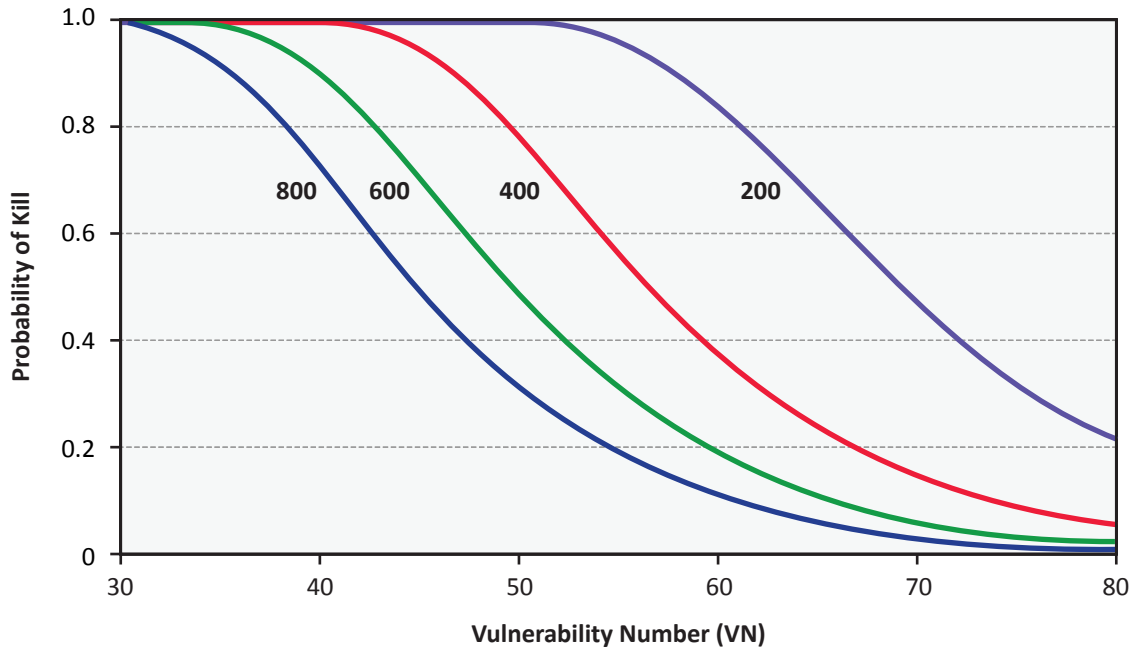
The Probability of Damage Calculator (PDCALC) is the US Department of Defense’s standard software for calculating the single-shot kill probability for a nuclear weapon on a single target. It is embedded in the US Strategic Command planning software used to evaluate the effectiveness of options for using nuclear weapons. The inputs to the software are weapon yield, weapon accuracy given by the CEP, desired ground zero (also known as aimpoint), target area, height of burst, uncertainty in height of burst, and the hardness of the target as given by the VNTK number.

Because more detailed information is classified, only a parametric treatment is possible in this report. The graphs below illustrate the impact of target hardness, weapon yield, and accuracy on single-shot kill probability against a hard point target such as an ICBM silo. The weapon is assumed to be 100 percent reliable. The hardness values are expressed in terms of VNTK and range from VN values of 30 to 80. The TK portion of VNTK is held constant across all of the subsequent graphs. The warhead explosive yield is held constant in Figure A-2 and Figure A-4. In Figure A-3, warhead yield (in kilotons) varies along the x axis. Figure A-5 shows single-shot kill probability versus CEP for a target with a hardness of 4,000 pounds per square inch, with several curves corresponding to different warhead yields.



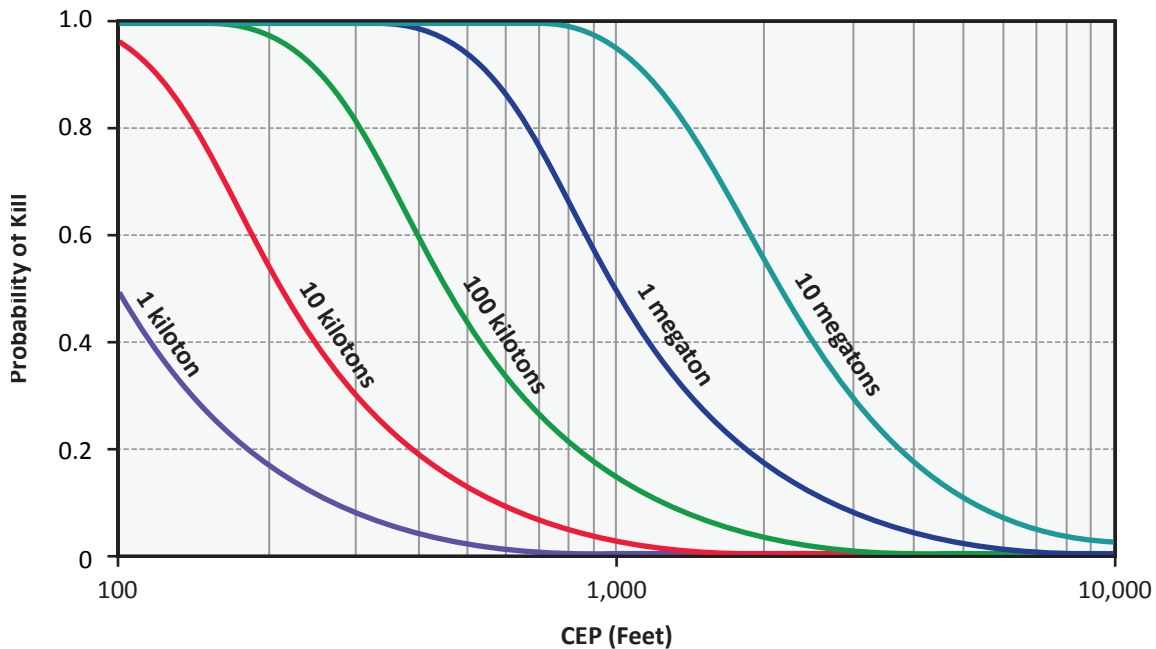
VN values from 30 to 80 in steps of 10, warhead reliability of 100 percent. One curve for each VNTK value. All curves are based on the same CEP.

Figure A-3. Probability of Kill vs. Weapon Yield



Curves for CEPs of 800, 600, 400, and 200 feet, 100 percent warhead reliability. One curve for each CEP value. All curves based on the same yield.

Figure A-4. Probability of Kill vs. VN of Target



Curves for yields ranging from 1 kiloton to 10 megatons. One curve for each yield value.

Figure A-5. Probability of Kill vs. CEP for a 4,000-Pound-per-Square-Inch Target

The figures show a strong relationship between target survivability and target hardness in cases with larger CEPs but a weaker correlation once the CEP gets below 200 feet. Survivability is invariably poor in the limit of extremely good CEP (such as 150 feet or less), at least for yields in the hundreds of kilotons. In other words, making silos harder may be a viable way to improve ICBM survivability if the CEP of missiles attacking those silos exceeds 150 feet.

Mobile ICBMs Deployed in the Field

As mentioned earlier, if the enemy cannot target individual mobile ICBMs, the key survivability issues include the following:

- The size of the operating area available to the mobile ICBMs
- The number and yield of the enemy reentry vehicles
 - Russia declared a force of 1,428 reentry vehicles on ballistic missiles under New START, and it would almost certainly be impossible to use 90 percent or more of these reentry vehicles to attack US ICBMs.
- The hardness of the mobile ICBMs, taken here to be in the range of 15 to 30 pounds per square inch (based on a RAND report)

Accuracy would not be a major factor if the lethal radius of the enemy reentry vehicle against a target with a hardness of 15 to 30 pounds per square inch were several times greater than the CEP. For yields of 100 to 500 kilotons and hardness values of 15 to 30 pounds per square inch, the lethal area (LA) varies from about 1.7 to 7.8 square kilometers, with lethal radii of about 740 to 1,580 meters.

If the total available operating area for the mobile ICBMs is denoted by OA, then the enemy's price to attack (denoted by PTA), exclusive of any extra reentry vehicles assigned to compensate for imperfect reliability or nonzero CEP, is approximately

$$PTA \cong 1.2 * OA / LA.$$

This formula is based on laying down the reentry vehicles in a hexagonal pattern with a CEP of zero. Unless the CEP of the enemy reentry vehicles is negligible in comparison with the lethal radius against a mobile ICBM, this number would grow to compensate for having the "little circles" drawn by the reentry vehicles not being perfectly aligned relative to the operating area.

The total area of the three US ICBM bases is on the order of 80,000 square kilometers, of which some fraction is probably unsuitable for deployment. With a simplistic assumption that 80 percent of the total area is usable, this leads to a usable operating area of 64,000 square kilometers. This indicates the need for anywhere from 10,000 to 45,000 reentry vehicles, even with a CEP of zero and perfect reentry vehicle reliability (the best case for the attacker). With a CEP of perhaps 150 meters and reliability of 80 percent, these numbers would grow significantly.

Although these values are somewhat uncertain, they are so far in excess of the maximum number of reentry vehicles available that the conclusion is still firm: a barrage attack against deployed mobile ICBMs is infeasible if the deployed ICBMs take full advantage of the available area.

Mobile ICBMs Deploying from a Garrison under Attack

The discussion above is appropriate to a situation in which the US ICBM force is on its maximum state of alert. In a day-to-day posture, however, a majority of the mobile ICBMs might be indoors in garrisons. The survivability of mobile ICBMs deploying from an aboveground garrison under attack depends on the following factors:

- The number and yield of the incoming warheads
- The number of US garrisons (more garrisons means fewer enemy warheads per garrison)
- The hardness of the vehicles carrying the mobile ICBMs
- The speed with which the ICBMs can get away from the garrison (considering how long it takes to receive an alarm, how long it takes the vehicles to get out of the garrison once an alarm sounds, and the top speed of the vehicles)
- Whether each garrison is surrounded by a spoke-like road geometry that allows mobile ICBMs to deploy in many directions at once
- Whether the ICBM vehicles have any off-road capability

If the mobile ICBMs can disperse in every direction from the garrison,¹ which would likely require that the mobile ICBMs be able to travel off road, then the upper limit on the area that the enemy needs to saturate around a garrison is

$$A = \pi * (v * T)^2.$$

¹ If some appreciable fraction of the ground near the garrison could not be traversed, then the available area would be less than that indicated by this formula.

In this formula, v is the average speed of the mobile ICBM after it exits the doors of the garrison, and T is the amount of time that elapses between the time the mobile ICBMs come out of the doors and the time that the enemy warheads detonate. The United States has no mobile ICBMs, and foreign mobile ICBMs are road based, so it is hard to quantify v , but 20–30 kilometers per hour seems qualitatively reasonable for off-road travel by a large-wheeled vehicle. The value of T would be approximately

$$T \approx 24\text{--}34 \text{ minutes (flight time of enemy missile)} - \text{time to get warning of enemy launch to the garrison} - \text{time for the ICBMs to get out the door upon receipt of warning.}$$

Taking into account all of the various uncertainties noted above, the value of A could be anywhere from about 50 to 500 square kilometers.

The number of nuclear weapons needed to eliminate each garrison would then depend on the yield of the enemy warheads and the hardness of the mobile ICBMs. For simplicity, we will assume that each reentry vehicle has a reliability of 100 percent, a CEP of zero, and a lethal area of 1.7–7.8 square kilometers. Using the same procedure described above for the barrage attack against deployed mobile ICBMs, we find that the enemy would need to use roughly 8–350 reentry vehicles against each US garrison. For a US force of 15–45 garrisons, this would correspond to anywhere from 120 to 16,000 reentry vehicles. Compensating for a nonzero CEP and for imperfect reliability would probably drive up the lower and upper bounds by another 50 percent or more. *Although there is considerable uncertainty in both the lower and upper bounds just presented, the lower bound is low enough and the upper bound is high enough to support the following conclusion: for an enemy attack involving 1,000 reentry vehicles, the survivability of the US off-road mobile ICBMs deploying under attack could be anywhere from zero to outstanding.*

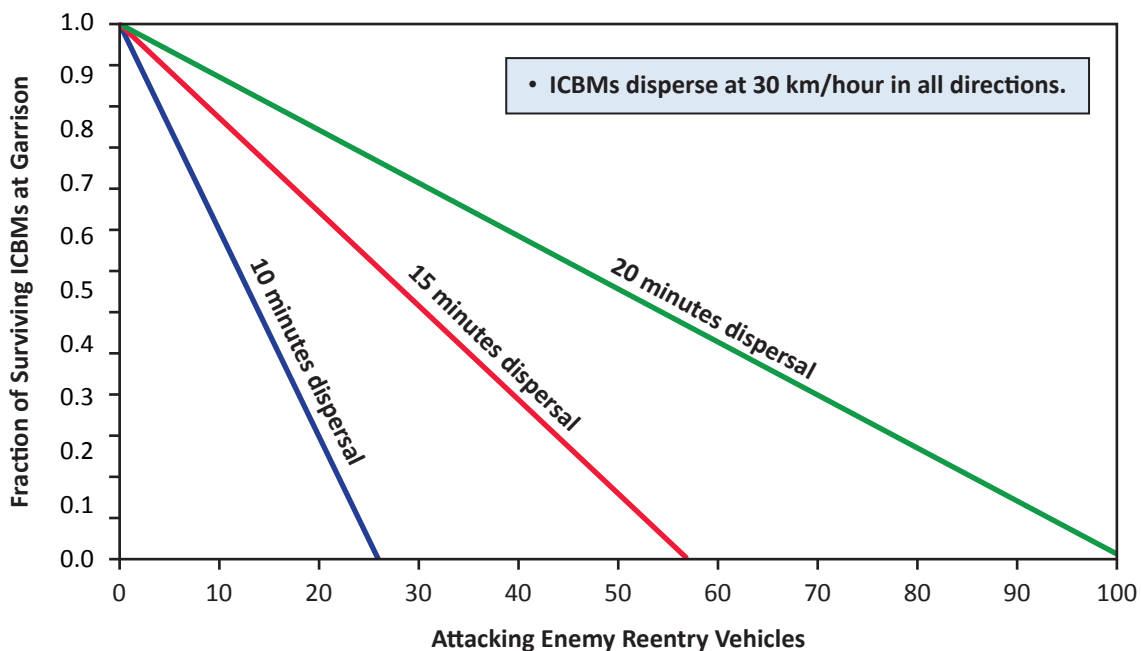


Figure A-6. Fraction of Surviving Mobile ICBMs vs. Number of Attacking Enemy Reentry Vehicles in an Attack on One Garrison

It is also possible to display this idea graphically. Consider a simplified attack against an ICBM garrison. Each attacking reentry vehicle has a notional lethal area of 5 square kilometers against a mobile ICBM. The reliability of the enemy reentry vehicles is set to 100 percent, and the CEP of the enemy reentry vehicles is assumed to be zero, so that the lethal circles produced by the reentry vehicles are perfectly aligned in a hexagonal pattern. (Alternatively, the value of the lethal radius could have been adjusted downward to reflect the nonzero CEP but still leading to an adjusted lethal area of 5 square kilometers.) Figure A-6 shows the fraction of the mobile ICBMs at the garrison that survive as a function of the number of attacking reentry vehicles. The three curves are for dispersal times of 10, 15, and 20 minutes, and the average ICBM off-road speed is 30 kilometers per hour. Figure A-7 shows the enemy’s price to attack against one garrison as a function of the amount of dispersal time and for dispersal speeds of 20 and 30 kilometers per hour.

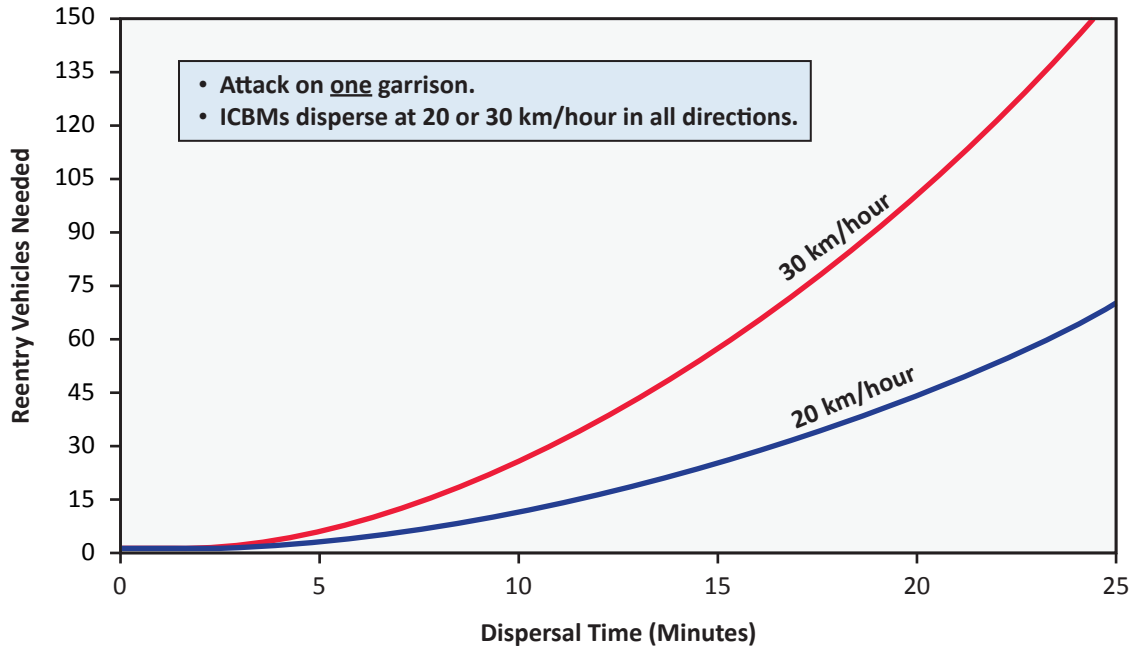
If the US mobile ICBMs are road based, then the enemy has to deal with only a linear problem. If the number of US garrisons is N_G and the number of road spokes leading away from each garrison is N_S (a number that might vary from one garrison to another in reality), then the length of road that the attacker has to cover is

$$L_{road} = v * T * N_G * N_S.$$

In the limit where the enemy reentry vehicles have a reliability of 100 percent and a CEP that is small in comparison to the lethal radius, the enemy’s price to attack would then be approximately

$$P \cong L_{road} / (2 * (LR - CEP)).$$

For speeds of 60–80 kilometers per hour, lethal radius values of 800–1,600 meters, a CEP of zero, dispersal times of 10–20 minutes, 15–45 garrisons, and 4–12 spokes leading away from each garrison, the number of perfectly reliable reentry vehicles needed to completely saturate the length of dispersal roads available could range from



Upper red curve = dispersal speed of 30 kilometers per hour. Lower blue curve = 20 kilometers per hour.

Figure A-7. Price to Attack against a Garrison for Mobile ICBMs

about 184 to 8,900. With a CEP of 100 meters and a reliability of 80 percent, the number of reentry vehicles needed would increase substantially, but probably by less than a factor of two. *As before, despite considerable uncertainty in both the upper and lower bounds, the lower bound is low enough and the upper bound is high enough to support the following conclusion: for an enemy attack involving 1,000 reentry vehicles, the survivability of the US road mobile ICBMs deploying from garrisons under attack could be anywhere from zero to outstanding.*

In summary, the survivability of mobile ICBMs deploying from garrison while under attack is completely uncertain, because the survivability depends on compounded uncertainties in multiple factors that have unknown, or highly uncertain, values.

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