Intercontinental Ballistic Missiles and Their Role in Future Nuclear Forces

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The DOD started the B-21 program for maintaining the bomber force, the *Columbia*-class ship, submersible, ballistic, and nuclear missile submarine (SSBN) program for the SSBN force, and the B61-12 program for maintaining nuclear bombs, and these programs have been under way for several years.[1] By contrast, intercontinental ballistic missiles (ICBM) recapitalization—in the form of the Ground-based Strategic Deterrent (GBSD) program—was not funded until fiscal year 2016. Details are currently lacking on program cost, missile characteristics, basing mode, and the planned size of the ICBM force in 2040. However, with a 2016 start and typical development times for large missiles, it is likely that the ICBM force will drop below the planned New Strategic Arms Reduction Treaty (START)-level of 400 missiles for some period in the 2030s even if the long-term goal is a force of 400 missiles or more. Similarly, the department has just started a program—the Long-range Standoff (LRSO) cruise missile program—for maintaining the air-launched cruise missile element of the triad. The DOD has expended almost no funding on either the ICBM program or the LRSO program to date. Moreover, providing full funding for these two programs in the 2020s—in competition with the B-21 bomber, F-35 fighter, KC-46 tanker, T-X trainer, and various satellites—will be challenging. Of the two relatively nascent programs, the GBSD will almost certainly involve much larger amounts of funding than the LRSO. Hence, although the recent *Nuclear Posture Review* (*NPR*) endorsed the GBSD program, the high cost of this program makes it likely that discussions on the future of the ICBM force will continue for several more years.[2]

This assessment presents technical analyses to help inform decisions on whether to retain an ICBM force beyond about 2035 and—if ICBMs will be retained—what characteristics would be desirable in a future ICBM force. This report also identifies policy issues that decision makers need to consider before making large acquisition choices or deciding on new treaties for nuclear weapons.

If the nation decides to retain ICBMs in the 2040s and beyond, the answers to three key questions will largely drive the desired force size and characteristics, although several other metrics (cost, in-flight survivability, payload, and so forth) also are relevant:

1. How survivable will future ICBMs need to be against a large and advanced attack? This question is discussed below, along with various options for improving ICBM survivability.
2. To what degree will future ICBMs need to reach Asian targets further than Russia, especially without flying over Russia? Techniques for achieving such a capability are discussed below in the section that discusses target coverage.
3. To what extent will future ICBMs need to balance lethality and collateral damage? In the future, high levels of collateral damage may be less acceptable than was the case during the Cold War, so it may be important to have accurate delivery options for low-yield weapons.

Also, it is important to compare entire strategic force structures, with variable numbers of ICBMs and other systems, and variable characteristics, instead of focusing purely on missile force structure and features. Finally, if the decision is to abandon the ICBM force by 2040, the nation needs to decide whether to procure more bombers, transatmospheric vehicles, SSBNs, nuclear cruise missiles, or something else (such as missile defense) to provide elements essential to future strategic forces in the absence of ICBMs. This study considered additional SSBNs as a compensation measure for eliminating or reducing ICBMs (in the section on force structure options).

Survivability against a Large Preemptive Counterforce Attack

When initially deployed, US silo-based ICBMs were highly survivable because of the poor accuracy of Soviet ballistic missiles in the 1960s and early 1970s.[3] However, Soviet/Russian missile accuracy has improved greatly in the last 40 years and will likely continue to do so in the future. So the US ICBM force may not be very survivable against a Russian attack in 2030 or beyond unless the US strategy is to rely on launching ICBMs based on warning of Russian missile launches. No other nation is likely to have a force with the number and accuracy of nuclear weapons needed to threaten US silo-based ICBMs in 2030, although China has the resources and technology to pose a threat by perhaps 2035 if Chinese leaders choose to expand their arsenal.[4]

The primary approaches to improving ICBM survivability are harder silos and mobile ICBMs. Launch-on-warning could also improve survivability relative to riding out an attack, but no meaningful discussion of this topic is possible in an unclassified forum. Also, launch-on-warning—if implemented successfully—would contribute to the initial retaliatory strike against the country that attacked the US but would not increase the number of US nuclear weapons available days or weeks after the initial foreign attack.

For a force of 400 or more ICBMs, harder silos would have substantial benefits in the next decade or two but could be vulnerable to credible future improvements in foreign missile accuracy. However, in a much smaller ICBM force of perhaps 150 silos, harder silos would be less likely to produce major benefits against a large and accurate attack because of the enemy's ability to aim multiple, accurate, high-yield weapons at each silo. The benefits of a silo-based ICBM force increase at least in a linear manner—and possibly faster—as a function of force size, whereas the overall costs of an ICBM force rise in a slower-than-linear manner. The slower increase is because research and development costs are largely independent of force size, as are the costs associated with annual flight tests of the missiles. Figure 1 illustrates a quantitative example of this dependency on force size. Suppose that an attacker wants to be sure that no more than 20 ICBM silos survive the attack, independent of the size of the US ICBM force. Suppose further that each attacking re-entry vehicle has a 70 percent single-shot kill probability. (The figure of 70 percent is notional but subjectively reasonable.) The figure 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 100–800. Such an increase in the number of ICBM silos increases the price to attack by a factor of nearly 17 (and to a number much more than US or Russian forces under New START).[5] If the first 200–400 attacking re-entry vehicles had a high single-shot kill probability, and all subsequent reentry vehicles had a much lower single-shot kill probability, the price to attack would grow more than indicated in figure 1.

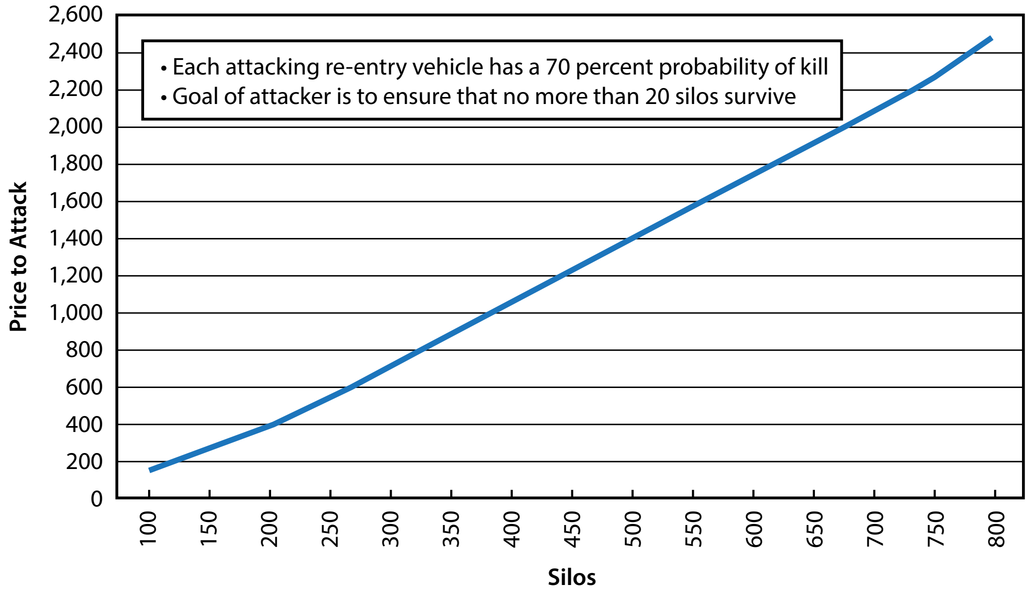

Figure 1. Enemy price to attack as a function of the number of US ICBM silos

Mobile ICBMs deployed in the field (outside of their garrisons) should be highly survivable unless the enemy can detect and track deployed ICBMs in real time. If the enemy had this capability, then mobile ICBMs would have poor survivability because they are soft targets. The survival rate for mobile ICBMs in the process of deploying from garrison under attack could vary widely—from poor to outstanding—depending on multiple factors that have uncertain values, including:

- The number of US garrisons (Unlike the case with silo-based ICBMs, the adversary's "price to attack" depends on the number of US garrisons, not the number of US missiles. Hence, the number of warheads available for saturating the operating area around each US garrison would be (M/N), where N is the number of US garrisons, and the number of enemy weapons available for attacking the garrisons is M.)
- How long it takes for the ICBM garrisons to receive warning of an incoming attack
- How quickly the ICBM launcher vehicles can leave the garrison once an alarm sounds
- Whether the ICBM launcher vehicles are limited to operating on roads
- The road geometry around the garrisons (multiaxis; spoke versus being limited to traveling in one of two directions on a single road)
- The top speed of the ICBM launcher vehicles
- The hardness of the ICBM launcher vehicles

The survivability of ICBMs is only part of the issue. Ensuring the survivability of an adequate portion of the overall nuclear force is a broader goal. SSBNs at sea are likely to be highly survivable for the next decade at least, whereas SSBNs in port are vulnerable even to a small nuclear attack by weapons of moderate accuracy. Also, SSBNs at dock are vulnerable to conventional cruise missiles. Bombers on maximum nuclear alert should be relatively survivable against a preemptive attack, but bombers are unlikely to be on nuclear alert, except in a severe and protracted crisis. As with SSBNs in port, bombers that are not on alert are quite vulnerable to a small nuclear attack by weapons that do not have state-of-the-art accuracy. Improved ballistic missile defense might be able to help with bomber and SSBN survivability against small attacks. Cruise missile defense at bomber and SSBN bases would also be beneficial because Russia has nuclear and conventional submarine-launched cruise missiles. Keeping one bomber base on nuclear alert at all times would be another useful measure.

Target Coverage

The survivability of the nuclear force is not, by itself, sufficient. Surviving nuclear weapons must be able to reach potential adversaries. The ability to do this depends on weapon range, in-flight survivability, and the extent to which overflight of countries other than the adversary is acceptable. No detailed discussion of in-flight survivability is possible in an unclassified setting, although ICBMs and SLBMs would be highly survivable unless the adversary has advanced ballistic missile defenses, such as, possibly, the defensive system around Moscow.

ICBMs provide good coverage of Russia from the current bases without having to fly over any other country, except Canada. When ICBMs were initially deployed in the 1960s, this was all they were designed to do, but the future world may require coverage of additional countries. As shown in figure 2, ICBMs at the current bases cannot reach much of Asia without flying over Russia. If ICBMs need to reach potential non-Russian adversaries without flying over Russia, there are three basic approaches: adding bases in Hawaii (or Guam) and Cape Canaveral, Florida,[6] providing a capability for maneuvers to divert around Russia, or building an ultra-long-range ICBM that flies a trajectory over the southern hemisphere and approaches some targets from the south. All three of these approaches are expensive, and the latter two are technically risky. Figure 3 depicts the impact of adding two more ICBM bases in Hawaii and Cape Canaveral.

By contrast, SSBNs and bombers are more capable of reaching various countries without having to fly over Russia. Therefore, it may be reasonable to accept this limitation in future ICBMs and rely on bombers, SSBNs, and possible future non-strategic nuclear systems for non-Russian targets.

Reaching regions in white or gray over Asia and the Indian Ocean requires an overflight of Russia. Results shown do not include any shadowing due to the small Russian enclaves in Kaliningrad and Crimea. The red ring in North America bounds the region containing the US bases. Missile range is varied parametrically.

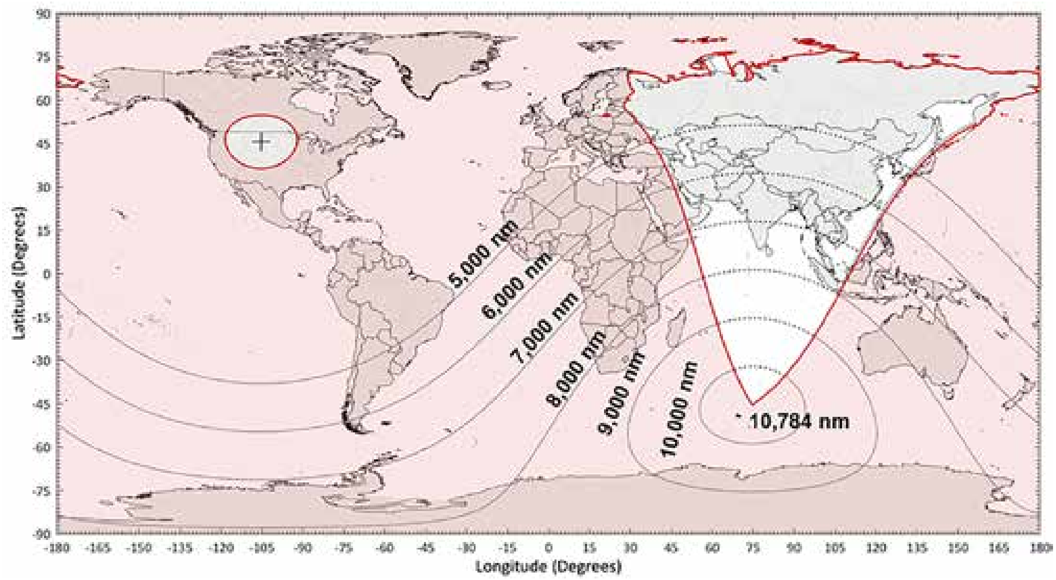

Figure 2. Target coverage from current ICBM bases without flying over Russia

Reaching regions in white or gray over Asia and the Indian Ocean requires an overflight of Russia. The ICBM has a notional range of 8,000 nautical miles. Varying the ICBM range parametrically would make this figure too cluttered. Results shown do not include any shadowing due to the Russian enclaves in Crimea and Kaliningrad.

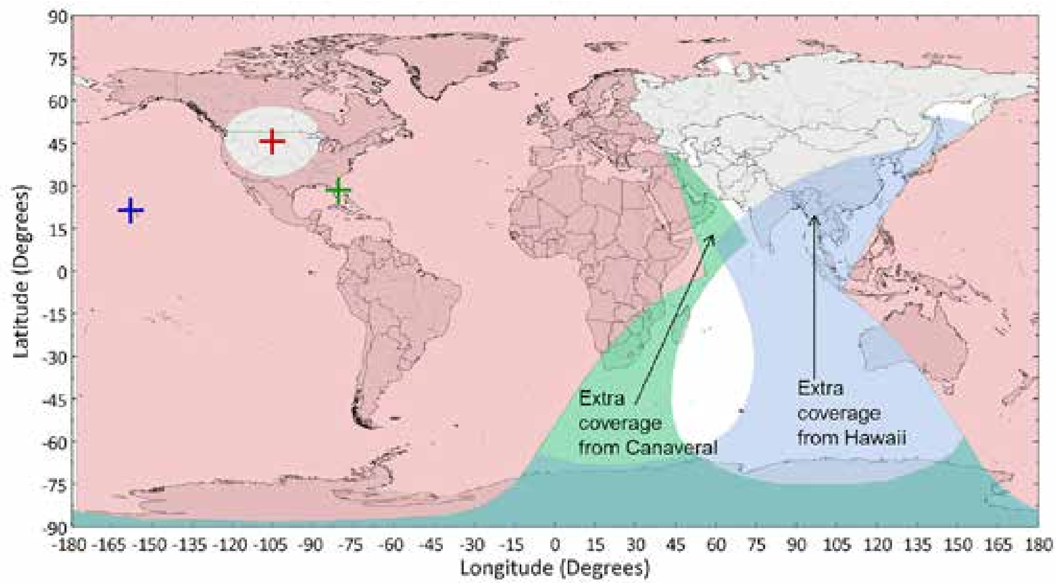

Figure 3. Target coverage with extra bases without flying over Russia

Weapon Lethality and Collateral Damage

In addition to the various factors previously discussed, it also is important for a US weapon to demonstrate a high probability of destroying its intended target. It may also be helpful to minimize the number of civilian casualties resulting from each US strike, both for moral reasons and to enhance deterrence by giving an adversary more reason to think that the US would use nuclear weapons if sufficiently provoked. For example, if the US could not destroy a target without inflicting civilian casualties that are grossly excessive in relation to any military goal, then an enemy might not believe that the US would conduct such an attack and would, therefore, not be deterred.[7] Prompt casualties depend on the population density around the target, weapon yield, height of burst, and (for a ground burst) wind direction. Lethality depends on accuracy, yield, and the ability to control the height of burst, with accuracy being the most important factor. Figures 4–5 illustrate this phenomenon and show that accurate, low-yield weapons can achieve high lethality against the vast majority of targets. (The two figures are not closely keyed to the actual hardness of real targets, although 21 pounds per square inch is near the upper limit for a small building.) Although these figures do not explicitly calculate collateral damage, it would often be possible to combine very high effectiveness with relatively low civilian casualties—at least if the targets are outside urban areas.

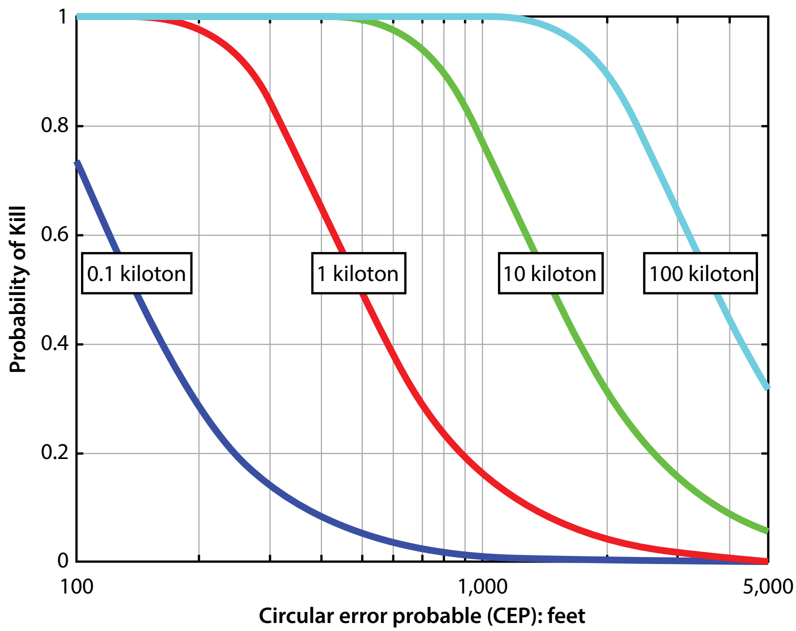

Figure 4. The probability of kill versus circular error probable (CEP) for a 21-pound per square-inch target

Note: X-axis=accuracy of the weapon, as measured by a CEP. Y-axis=probability of destroying the target. Each curve represents a warhead of the indicated yield (range of 0.1–100 kilotons) with a reliability of 100 percent.

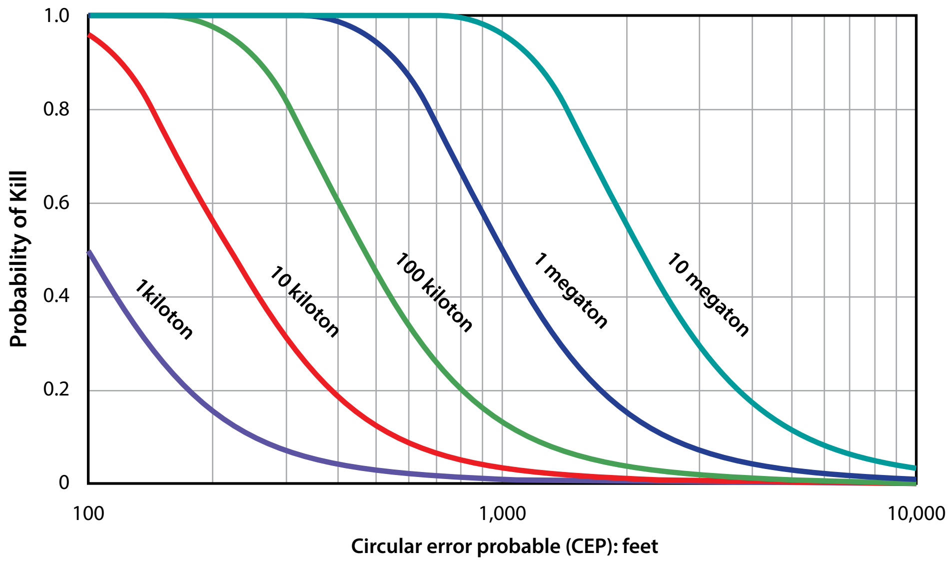

Figure 5. The probability of kill versus CEP for a 4,000-pound per square-inch target

Note: Curves for yields ranging from 1 kiloton to 10 megatons, with one curve for each yield and a reliability of 100 percent.

However, it should be noted that ICBMs and SLBMs might not always be the preferred weapons in cases where there is a need to maximize the ratio of lethality to collateral damage. It would likely be easier to achieve a CEP (a measure of accuracy) of perhaps 30 to 150 feet in a guided bomb or a cruise missile than in a long-range ballistic missile, although the ballistic missiles would have significant advantages in speed of response and in-flight survivability.

Force Structure Options

When making decisions on future nuclear forces, it is not sufficient to consider the performance of individual triad legs; it is necessary to compare plausible complete force structures. Consequently, we examined seven triads (with 150–510 ICBMs and 8–12 SSBNs) and four bomber-SSBN dyads (with 10–18 SSBNs) in the context of a major nuclear war against an adversary with a large and fairly accurate inventory of nuclear weapons. (We also examined a much smaller attack of 50–100 re-entry vehicles. This is less than the number of US ICBMs in any of the triads, so this small notional attack was limited to SSBN bases, bomber bases, and other non-ICBM targets.) For simplicity, we designed all forces to comply with New START limits, although the New START Treaty will expire in 2021, absent an agreement to extend it. Some of the forces, in fact, are well below New START limits and would likely comply with the limits in any plausible successor treaty.

The forces chosen span a reasonable set of ICBM-SSBN trades. It would also be desirable to evaluate trades between bombers and ballistic missiles, but such trades were not considered because of uncertainty about weapon loads for the B-21 bomber and about the number of LRSO cruise missiles carried by the B-2 and the B-52. (It is necessary to know how many bomber *weapons* survive a preemptive enemy attack and successfully penetrate any defenses en route to the weapon launch point, not simply the number of bombers.) Hence, all forces considered have 60 deployed nuclear-capable bombers, although it would be possible to deploy a much larger number of bombers in the dyads and the triad with only 150 ICBMs without exceeding any New START limits.[8]

The table lists the 11 forces that were studied by the Johns Hopkins University Applied Physics Laboratory (JHU/APL). Two force structures in the table include more than 12 SSBNs. These extra SSBNs would not be available until after 2042 unless the US accelerated procurement of the *Columbia*-class SSBNs. By contrast, all of the ICBM options could be available by 2040. The primary metric for comparing these forces was survivability against a counterforce attack. All options provide good target coverage and timeliness. Comparisons on other metrics would be more illuminating if the forces varied the number of bombers but are less relevant to trades between ICBMs and SLBMs.

Table. Force structure options (60 bombers in all cases)

Force options	*ICBMs*	*SSBNs*	*Accountability versus actual warheads*	*Delivery vehicles*
0[a]	0	10	860/1,280	220
1[a]	0	12	1,020/1,440	252
2[a]	0	14	1,180/1,600	284
3[a]	0	18	1,500/1,920	348
4[b]	400	12	1,420/1,840	652
5[c]	510	8	1,550/1,970	698
6[c]	480	10	1,550/1,970	700
7[c]	400	12	1,550/1,970	652
8[c]	448	12	1,550/1,970	700
9[c]	150	12	1,550/1,970	402
10[d]	148	12	1,468/1,888	700

Source: JHU/APL

a Bomber-SSBN dyads

b Single-warhead ICBMs in current silos and launch control centers

c New ICBMs in new, harder silos and new, harder launch control centers. Some ICBMs carry multiple warheads, but are consistent with New START limits. Options 4–8 have 1–3 warheads per missile. Option 9 has a larger missile with up to 5 warheads.

d Mobile single-warhead ICBMs

Our modeling suggests that a triad is better than a dyad, at least of similar or lesser cost, according to most metrics. However, the triad–dyad choice depends on which characteristics are more important to decision makers, or specifically:

- Relative to triads of similar procurement cost, bomber-SSBN dyads may perform well regarding the number of surviving US weapons if the US forces are on maximum alert at the time of a large and accurate nuclear attack.[9]
- Triads, by contrast, perform considerably better than bomber-SSBN dyads of similar cost regarding the number of surviving US weapons if the US forces are in a day-to-day posture at the time of a large and accurate enemy attack. Dyads could be improved to some extent by having a higher day-to-day alert level for both bombers and SSBNs, but this would come at a cost and could interfere with prompt bomber availability for conventional missions.
- 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 (without regard for the alert status of US forces at the time of the small enemy attack).
- Additional metrics such as target coverage, lethality, collateral damage, and inflight survivability are important for the nuclear force as a whole but are not very helpful for selecting between ICBMs and SLBMs/SSBNs. Such metrics would, however, come into play in any attempt to evaluate trades between bombers and ballistic missiles.

Finally, it is also important to consider sensitivity to changes in threats and assumptions. For example, the bomber-SSBN dyads and the very expensive triad with mobile ICBMs are sensitive to improvements in an enemy's ability to detect and track mobile ICBMs, SSBNs at sea, or both, whereas silo-based ICBMs are not sensitive to such improvements but are quite sensitive to improvements in enemy missile accuracy.

Conclusions and Observations

Russia is modernizing its nuclear forces, and additional US investment will be needed to ensure parity with Russia if parity is deemed to be essential. Parity includes considerations of force size and also survivability, target coverage, and the variety of capabilities provided (yield, accuracy, reliability, the speed of response, and so forth). Parity considerations could be limited to strategic nuclear weapons, or they could be extended to include nonstrategic nuclear weapons, where Russia has a large advantage.

Analysis indicates that a well-designed triad is superior to a bomber-SSBN dyad in terms of the post-exchange balance of weapons after an enemy counterforce attack, survivability against a small enemy attack, and the price to attack imposed on a foreign great nuclear power. Under some conditions, by contrast, a dyad can be comparable to a well-designed triad regarding the number of US weapons that would survive a counterforce first strike.

US ICBMs at the current bases provide good coverage of Russia, but ICBMs would have to fly over Russia to reach other countries in Asia. (This is a purely technical observation; the authors take no position on the likelihood that an ICBM overflight of Russia would be permitted.)

The benefits of the ICBM force increase linearly or faster as a function of the ICBM force size, whereas total ICBM costs increase in a slower-than-linear manner as a function of the ICBM force size. Hence, it would be desirable to retain all three ICBM bases and at least 400 ICBMs. For example, it would be possible to have a force of 448 ICBMs, in conjunction with 12 *Columbia*-class SSBNs and 60 deployed nuclear bombers, without violating New START limits.

It may also be important to consider US nuclear needs—both strategic and nonstrategic—for adversaries other than Russia. Deterrence of geographically small adversaries poses special challenges (due to fallout propagation from high-yield ground bursts), which would be necessary for negating underground targets.

These conclusions are derived from physics-based analyses, and they should be integrated with deterrence theory and policy considerations to provide the best input to major investment decisions. In particular, decisions on the future of the ICBM force depend in large part on policy questions that physics-based modeling can help inform. Key policy questions include the following:

1. What level of threatened retaliation against which potential adversaries is adequate to support US deterrence strategy?
2. How should the US think about Russia in the future, including issues of overflight and future treaties?
3. How much is the nation willing to invest in its nuclear force?
4. How survivable should ICBMs be against a large and advanced attack?
5. How important is it to deplete an adversary's nuclear stockpile in an exchange to influence the post-exchange balance of weapons?
6. Under what conditions might the nation select a bomber–SSBN dyad?

This analysis focused on strategic nuclear forces, especially ballistic missiles. Russia is also devoting considerable effort to developing and producing accurate, low-yield nonstrategic nuclear weapons. The US does not have any development programs for similar weapons, except for the B61-12 bomb for the F-35A, the B-2, and, eventually, the B-21. Russian use of such weapons could have military advantages that might negate US/North Atlantic Treaty Organization superiority in conventional weapons and/or force the US into a disproportionate response. Additional analyses are warranted on nonstrategic nuclear weapons, including considerations on the extent to which the LRSO cruise missile could compensate for Russian advantages in nonstrategic nuclear weapons.

The value of the analyses conducted by JHU/APL derives from a focus on physics-based modeling, a subset of quantitative analysis that relies on first-principle calculations of variables such as weapons' survivability, lethality, and ability to reach targets. Although the work performed in this study cannot answer critical policy questions, quantitative modeling assists decision makers by providing the discernment to answer some policy questions and to render policy objectives more quantifiable. This synergistic process of quantitative modeling and policy refinement would naturally enhance acquisition decisions, force structure decisions, future versions of the *NPR* and similar studies, and future arms control negotiations. ✪

Notes

1. Jeremiah Gertler, "Air Force B-21 Raider Long-Range Strike Bomber," *Congressional Research Service* (CRS), 7 June 2017, https://fas.org/sgp/crs/weapons/R44463.pdf; Ronald O'Rourke, "New *Columbia*-Class (Ohio Replacement) Ballistic Missile Submarine (SSBN[X]) Program: Background and Issues for Congress," *CRS*, 12 May 2017, https://fas.org/sgp/crs/weapons/R41129.pdf; and Amy F. Woolf, "U.S. Strategic Nuclear Forces: Background, Developments, and Issues for Congress," *CRS*, 10 February 2017, https://fas.org/sgp/crs/nuke/RL33640.pdf.

2. The future of the long-range stand-off cruise missile (LRSO) program is a major issue in its own right, even though the amount of funding involved would likely be 5–10 times lower than for the ground-based strategic deterrent program.

3. Dietrich Schroeer, *Science, Technology, and the Nuclear Arms Race* (Hoboken, NJ: John Wiley and Sons, 1984), 143–49.

4. Eric Heginbotham et al., *China's Evolving Nuclear Deterrent* (Washington, DC: RAND Corporation, 2017), https://www.rand.org/pubs/research_reports/RR1628.html.

5. This faster-than-linear increase in the enemy's price to attack occurs because—as the number of US intercontinental ballistic missiles (ICBM) grows—the enemy has to destroy a steadily higher percentage of the US ICBMs to hold the number of surviving US ICBMs to 20 or fewer. If the US forces consisted of only 66 ICBMs, the enemy would have to destroy only 70 percent of the US ICBMs to hold the number of survivors down to 20. With a single-shot probability of kill of at least 70 percent for the enemy missiles, this would require only one enemy missile per US silo. With 800 US ICBMs, the enemy would have to destroy 97.5 percent of the US silos. With a single-shot probability of kill of 70 percent for the enemy missiles, this would require three enemy missiles for every US silo and a fourth enemy missile for some silos.

6. A base on the west coast would not provide much additional coverage of countries in Asia without flying over Russia. A base in Guam would provide additional coverage than the base in Hawaii, that is assumed in figure 3, but at the expense of greater vulnerability to attack.

7. The Law of Armed Conflict forbids the use of weapons or tactics that cause noncombatant casualties that are disproportionate to the military objective achieved. *Disproportionate* is, of course, a subjective term, but an accurate, low-yield nuclear weapon would appear to be more compliant with this provision than an inaccurate, high-yield weapon, especially if there were a large number of civilians relatively close to the target. Similarly, the use of an inaccurate conventional missile (such as the Iraqi Scuds from Operation Desert Storm) would be permitted against an isolated military base but not against a military target in a city.

8. The programs for the *Columbia*-class nuclear-powered, ballistic missile-carrying submarine (SSBN) and the B-21 bomber have been underway for several years, and there is a consensus on the need for SSBNs in the nuclear mission (due to their survivability when at sea) and the need for a new, more survivable bomber in the conventional mission. Moreover, the cost savings from making the B-21 "conventional only" would be a small fraction of the total cost associated with the B-21, so it is not likely that the B-21 will lack nuclear capability (at least within the confines of New Strategic Arms Reduction Treaty [START] limits and counting rules). Hence, we did not consider bomber-ICBM or SSBN-ICBM dyads.

9. There are at least two ways to improve the survivability of a bomber-SSBN dyad: defenses against small attacks (ballistic or cruise missiles) and a day-to-day enhanced alert posture that keeps the maximum possible number of SSBNs at sea continuously and keeps one bomber base on ground alert at all times. This statement does not account for the costs associated with either defenses against small attacks or an enhanced alert posture for the bomber-SSBN dyad. The comparison of forces on maximum alert is based on the assumption of a lengthy crisis that naturally gave the dyad time to get all operational bombers on ground alert and to get all SSBNs to sea (exclusive of SSBNs in long-term

maintenance). If one were to include costs for defenses against small attacks and additional operating costs for an enhanced alert posture, then a bomber-SSBN dyad might be more expensive than a triad of comparable overall utility.

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