CHAPTER3

Escaping Stalemate

The New Era of Counterforce

The previous chapter suggests that countries need to build robust nuclear arsenals to create stalemate with their adversaries. Since nuclear stalemate is based on the threat of retaliation, an arsenal must be able to survive an enemy first strike and still inflict unacceptable damage on the attacker. Building such an assured retaliatory force is a major challenge; as the Cold War case demonstrates, the road to stalemate can be long, dangerous, and highly competitive.

Once nuclear-armed countries establish secure second-strike forces, are those countries truly safe? Can they stop arms racing and abandon all the other kinds of costly competitive behaviors that have defined international relations? Or are there incentives that compel them to compete even after they have built survivable arsenals? To restate the central puzzle of the nuclear age, why has intense geopolitical competition continued even under conditions of stalemate?

This chapter advances a second explanation for the puzzle: stalemate is reversible. For countries to relax and abandon the geopolitical strategies of the prenuclear age—that is, to stop worrying about shifts in the balance of power, engaging in arms races, and competing for alliance partners and strategic territory—nuclear-armed countries would need to be confident that the condition of stalemate is irreversible. In reality, however, countries can escape from stalemate. Therefore, even well-armed nuclear countries continue to engage in military competition. They compete to prevent adversaries from developing effective disarming strike capabilities, and in some cases they compete to build first strike capabilities themselves.

The reversibility of stalemate explains much of the competition in the last decades of the Cold War—as well as an increase in great power competition today. During the Cold War, the Soviet development of a survivable retaliatory force in the 1960s did not end or even dampen the nuclear arms race; instead, it triggered decades of intense U.S. efforts to track and target Soviet nuclear forces, to give the United States a war-winning option if deterrence failed. Those highly-classified U.S. efforts were more effective than most analysts have appreciated, and they explain much of the U.S. and Soviet arms racing behavior until the end of the Cold War. Today new technologies are increasing the vulnerability of nuclear forces around the world—unleashing renewed competition among the major nuclear powers.

In short, nuclear weapons are the best tools of deterrence ever created, but they do not negate the incentives for countries to engage in intense geopolitical competition. The fear that adversaries might acquire disarming strike capabilities—and the opportunity to acquire those counterforce capabilities for themselves—helps explain why international competition is alive and well in the nuclear age.

This chapter focuses on the efforts of nuclear-armed countries to exploit new technologies to escape from stalemate. To explore the links between technology and stalemate, we first describe the main strategies that planners employ to ensure arsenal survivability. Next, we explore one of the major technological trends eroding survivability today—the great leap in weapons accuracy—and illustrate how improved accuracy creates new possibilities for disarming strikes. We then focus on another major current trend—dramatic improvements in remote sensing—and explain how the resulting increase in transparency threatens concealed and mobile nuclear forces. We conclude with a summary of our findings and their implications for geopolitics in the nuclear age.

Nuclear Survivability in Theory and Practice

Analysts often take the survivability of nuclear retaliatory forces for granted, perhaps with good reason. Successful "counterforce" attacks (those aimed at destroying enemy nuclear forces) appear impossible once countries deploy large and dispersed arsenals, since nuclear weapons are easy to hide and protect.[1] Some analysts argue that even moderate numbers of deployed weapons are inherently survivable.[2] According to the arguments, survivability is a one-way street: once an arsenal becomes survivable, it never goes back.

What if this confidence in the survivability of nuclear arsenals is misplaced? What if survivability is reversible? If arsenal survivability depends on the uncertain course of technological change and the efforts of adversaries to develop new technologies, states will feel compelled to arms race to ensure that their deterrent forces remain survivable in the face of adversary advances. They will worry about relative gains, because a rich and powerful adversary will have more resources to invest in technology and military forces. They will value allies, which help contribute resources and valuable territory. Moreover, states may be enticed to develop their own counterforce capabilities in order to disarm their adversaries or limit the damage those adversaries can inflict in case of war.

In short, if nuclear stalemate can be broken, one should expect countries to act as they always have when faced with military threats. They will try to exploit new technologies and strategies for destroying adversary capabilities. They will eye each other’s economic power and military capabilities warily; strive for superiority over their adversaries in conventional and nuclear armaments; aim to control strategically relevant territory; seek to build and maintain alliances; and prepare for war. If survivability and stalemate are reversible, then the central puzzle of the nuclear era—continued geopolitical competition—is no longer a puzzle.

We argue not only that stalemate is reversible in principal, but also that changes in technology—rooted in the computer revolution—are making all countries’ arsenals more vulnerable than they were in the past. The fear of suffering devastating retaliation will still do much to deter counterforce attacks, but countries will increasingly worry that their adversaries are trying to escape stalemate, and they will feel pressure to do the same. Deterrence will weaken as arsenals become more vulnerable. In extreme circumstances—for example, if an adversary threatens escalation (or begins to escalate) during a conventional war—the temptation to launch a disarming strike may be powerful.[3] In stark contrast to the expectations of the nuclear peace, security competition not only has endured but also will intensify as enhanced counterforce capabilities proliferate.

Military planners have employed three basic approaches to protect their countries’ nuclear forces from attack: hardening, concealment, and redundancy. “Hardening” refers to the deployment of nuclear forces (such as delivery systems, warheads, and command sites) in reinforced structures that are difficult to destroy. For example, planners deploy missiles in reinforced silos designed to resist blast, heat, ground shock, and the other effects of nuclear detonations; place aircraft in hardened shelters; create protective sites for patrolling mobile missile launchers; and bury command-and-control sites, as well as the secure means used to communicate launch orders.

Nuclear planners also rely heavily on concealment, by which we mean efforts to prevent adversaries from identifying or locating one’s forces (such as through the use of camouflage, decoys, and especially mobility). Concealment is the foundation of survivability for mobile delivery systems, such as ballistic missile submarines (SSBNs) or mobile missile launchers (known as transporter erector launchers, or TELs), both of which hide in vast deployment areas. Aircraft are harder to hide because they require airfields for takeoff and landing, but they too can employ concealment by dispersing to alternate airfields or remaining airborne during alerts. Even the most difficult facilities to hide, hardened missile silos and command bunkers, can be concealed using camouflage and decoys.

Finally, redundancy is used to bolster every aspect of the nuclear mission, especially force survivability. Most nuclear-armed states use multiple types of delivery systems and warheads to complicate enemy strike plans and protect against warhead design flaws. They spread their forces and warheads across multiple bases. Moreover, the most powerful nuclear-weapon states employ redundant communication networks, command-and-control arrangements, and early warning systems.

No single strategy of survivability is ideal because each entails important trade-offs. Hardening is attractive, but it comes at the price of concealment—for example, it is difficult to hide the major construction entailed in building a nuclear silo. Also, hardened sites are not mobile; once discovered, they remain so.[4] Similarly, concealment comes at the price of hardening. If mobile forces are discovered, they tend to be easy to destroy. Concealment has another significant drawback: it is a “fail deadly” strategy, meaning that if an adversary develops a way to locate one’s forces, one’s arsenal might go from highly survivable to completely vulnerable almost overnight. Even worse, one might not know that the nuclear balance has shifted in such a calamitous manner.[5] Some countries have adopted operating doctrines that attempt to capitalize on the advantages of both hardening and concealment; for example, China today appears to be planning to distribute its mobile missiles in a nuclear crisis from its peacetime garrisons to remote protective sites.[6] Such approaches capture the benefits of both strategies, but they also pay the costs. For example, China's strategy leaves its forces vulnerable if an attacker has identified its dispersal sites or detects mobile missiles in transit.[7]

Major technological trends are directly undermining these strategies of survivability. Leaps in weapons accuracy threaten nuclear forces that rely on hardening, while an unfolding revolution in remote sensing threatens nuclear forces that depend on concealment. (Another major change since the end of the Cold War, far smaller nuclear arsenals among potential adversaries, weakens the third strategy of survivability, redundancy.)[8] The consequences of pinpoint accuracy and new sensing technologies are numerous, synergistic, and in some cases nonintuitive. Taken together, these developments are making the task of securing nuclear arsenals against attack much more challenging. Developing survivable forces is not impossible, but a new age of vulnerability has begun.

To be clear, nuclear arsenals around the world are not becoming equally vulnerable to attack. Countries that have considerable resources can buck these trends and keep their forces survivable, albeit with considerable cost and effort. Other countries, however—especially those facing wealthy, technologically advanced adversaries—will find it increasingly difficult to secure their arsenals, as guidance systems, sensors, data processing, communication, artificial intelligence, and a host of other products of the computer revolution continue to improve.[9]

One might think that only weak countries need to worry about an adversary "escaping stalemate"; surely, powerful countries have the resources to thwart any adversary's efforts to attain nuclear superiority. But history is not reassuring. In the Cold War, once the Soviet Union had built robust nuclear retaliatory forces, many observers assumed that stalemate could not be undermined and that U.S. leaders would recognize and respect the "objective" reality that mutual assured destruction was a permanent fact. Instead, American officials constantly sought counterforce weapons and technologies to gain a disarming first-strike or significant damage-limitation capability—such as more accurate missiles, missiles with multiple independently targetable reentry vehicles (MIRV), sensors for hunting mobile missiles at sea and on land, and a variety of weapons and innovations designed to undermine Soviet command-and-control and early warning systems.[10] By the end of the Cold War, Soviet leaders had little faith in their own retaliatory capabilities.[11] In the post–Cold War world, both Russia and China—America's two biggest nuclear competitors—have had good reason, at times, to fear for the survivability of their arsenals.[12]

Counterforce in the Age of Accuracy

For most of the nuclear age, neither bombers nor ballistic missiles could deliver weapons accurately enough to reliably destroy hardened targets. Too many variables affected the impact point of a bomb—such as the aircraft's speed and altitude; the air defense environment; and atmospheric conditions including wind, temperature, and humidity—for even highly skilled crews to deliver bombs precisely.[13] Long-range ballistic missiles were even less accurate. Although their initial deployment conjured fears of "bolt-from-the-blue" disarming strikes, throughout the 1970s long-range missiles were not accurate enough to destroy fields of hardened silos.[14]

Technological improvements chipped away at the sources of inaccuracy, however. Leaps in navigation and guidance, including advanced inertial sensors with stellar updates, improved the ability of missiles to precisely determine their positions in flight and guide themselves, as needed, back onto course. Other breakthroughs allowed mobile delivery systems, such as submarines and mobile land-based launchers, to accurately determine their own positions prior to launch, greatly improving their accuracy.[15] As a result of these innovations, new missiles emerged in the mid-1980s with far better accuracy than their predecessors, rendering hardened targets vulnerable as never before. For bombers, onboard computers now continuously measure the variables that previously confounded bombardiers. Data on aircraft speed and location are uploaded from the aircraft into the computers of bombs and cruise missiles, which in turn automatically plot a flight path from the release location to the target. The weapons adjust their trajectory as they fly to remain on course.[16] As a result, bombs and missiles can achieve levels of accuracy unimaginable at the start of the nuclear age.

The leap in munitions accuracy has been showcased repeatedly during conventional wars; videos of missiles and bombs guiding themselves directly to designated targets now appear mundane. Although the effects of the accuracy revolution on nuclear-delivery systems are equally dramatic, they have received far less attention, despite huge implications for the survivability of hardened targets.

IMPROVED MISSILE ACCURACY

Figure 3.1 illustrates one consequence of the accuracy revolution, as applied to nuclear forces, by comparing the effectiveness of U.S. ballistic missiles in 1985 to those in the current U.S. arsenal.[17] We use formulas that have been employed by nuclear analysts for decades to estimate the effectiveness of missile strikes against a typical hardened silo.[18] The figure distinguishes three potential outcomes of a missile strike: hit, miss, and fail. “Hit” means that the warhead detonates within the lethal radius (LR) of the aimpoint, thus destroying the target. “Miss” means that the warhead detonates outside the LR, leaving the target undamaged. “Fail” means that some element of the attacking missile system malfunctioned, leaving the target undamaged.

Figure 3.1 shows that the accuracy improvements of the past three decades have led to substantial leaps in counterforce capabilities. In 1985 a U.S. intercontinental ballistic missile (ICBM) had only about a 54 percent chance of destroying a missile silo hardened to withstand 3,000 pounds per square inch (psi) overpressure. In 2019 that figure exceeds 74 percent. The improvement in submarine-launched weapons is starker: from 9 percent to 80 percent (using the larger-yield W88 warhead).

Figure 3.1 also suggests, however, that despite vast improvements in missile accuracy, the weapons still are not effective enough to be employed individually against hardened targets. Even modern ballistic missiles are expected to miss or fail 20 to 30 percent of the time. The simple solution to that problem, striking each target multiple times, has never been a feasible option because of the problem of fratricide—that is, the danger that incoming weapons might destroy or deflect each other.[19] The accuracy revolution, however, also offers a solution to the fratricide problem, opening the door to assigning multiple warheads against a single target, and thus paving the way to disarming counterforce strikes.

THE FADING PROBLEM OF FRATRICIDE

One type of fratricide occurs when the prompt effects of nuclear detonations—radiation, heat, and overpressure—destroy or deflect nearby warheads. To protect those warheads, targeters must separate the incoming weapons by at least three to five seconds.[20] A second source of fratricide is harder to overcome. Destroying hard targets typically requires low-altitude detonations (so-called groundbursts), which vaporize material on the ground. When the debris begins to cool, six to eight seconds after the detonation, it solidifies and forms a dust cloud that envelops the target. Even small dust particles can be lethal to incoming warheads speeding through the cloud to the target. Particles in the debris cloud take approximately twenty minutes to settle back to ground.[21]

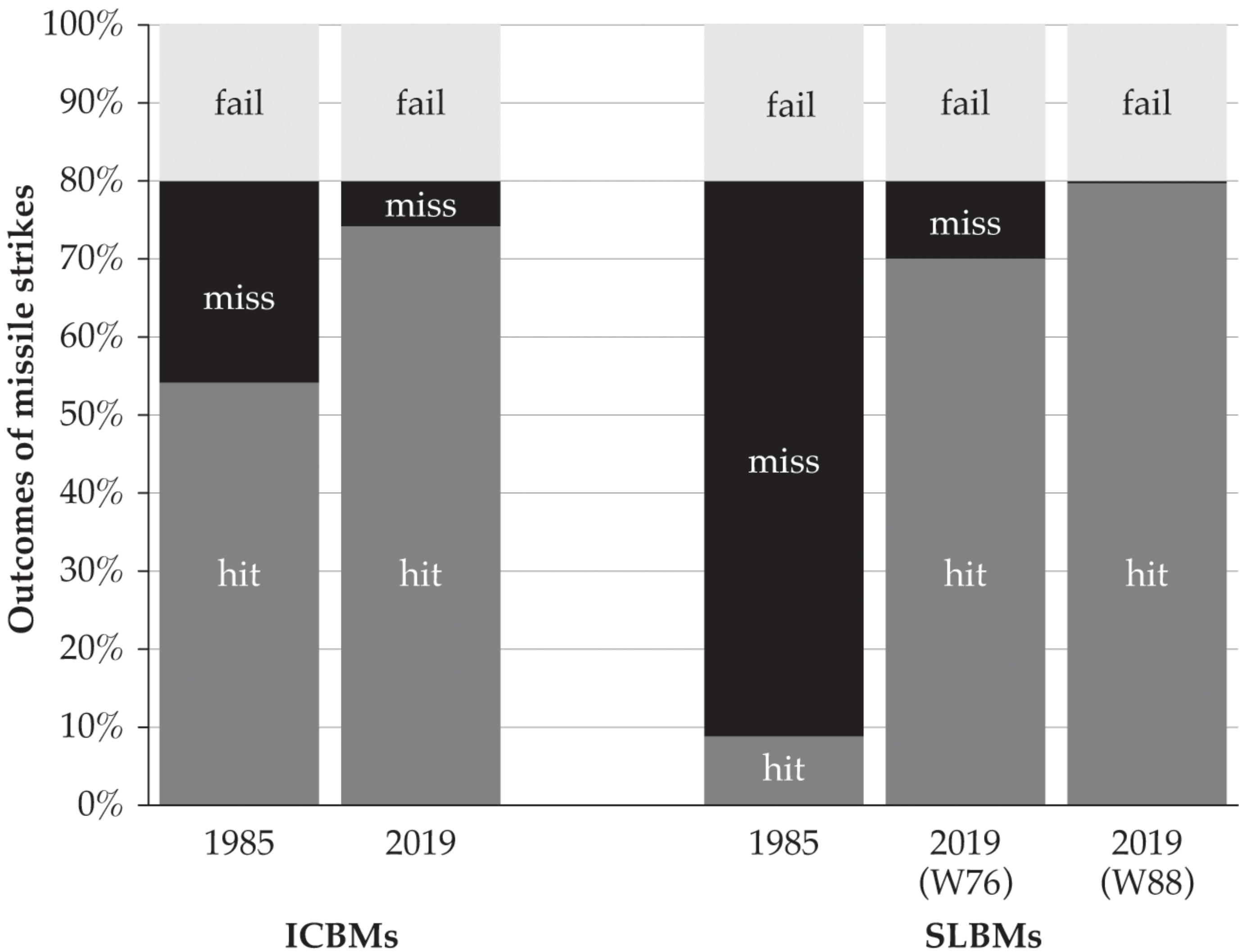

Figure 3.1. The growing vulnerability of hard targets, 1985–2019

Note: The calculations assume targets hardened to withstand 3,000 pounds per square inch (psi). Data for 1985 are based on the most capable U.S. land-based intercontinental ballistic missile (ICBM) and submarine-launched ballistic missile (SLBM) at the time: the Minuteman III ICBM armed with a W78 warhead and the Trident I C-4 SLBM armed with a W76 warhead. The 2019 ICBM data are based on the same Minuteman III/W78, with an improved guidance system. The 2019 SLBM data show both contemporary configurations of the Trident II D-5 missile: one version armed with the W76 and the other with higher-yield W88 warheads.

[22]

For decades, these two sources of fratricide, acting together, posed a major problem for nuclear planners. Multiple warheads could be aimed at a single target if they were separated by at least three to five seconds (to avoid interfering with each other); yet, all inbound warheads had to arrive within six to eight seconds of the first (before the dust cloud formed). As a result, assigning more than two weapons to each target would produce only marginal gains; if the first one resulted in a miss,[23] the target would likely be shielded when the third or fourth warhead arrived.

Improvements in accuracy, however, have greatly mitigated the problem of fratricide. As figure 3.1 shows, the number of misses—the main culprit of fratricide—is falling. To be clear, some weapons will still fail; that is, they will be prevented from destroying their targets because of malfunctioning missile boosters, faulty guidance systems, or defective warheads. Those kinds of failures, however, do not generally cause fratricide, because the warheads do not detonate near the target. Only those that miss—that is, those that travel to the target area and detonate outside the LR—will create a dust cloud that shields the target from other incoming weapons. In short, leaps in accuracy are essentially reducing the set of three outcomes (hit, fail, or[24] miss) to just two: hit or fail. The “miss” category, the key cause of fratricide, has virtually disappeared.

THE CUMULATIVE CONSEQUENCES FOR COUNTERFORCE

The end of fratricide is just one development that has helped negate hardening and increased the vulnerability of nuclear arsenals. The computer revolution has led to other improvements that, taken together, significantly increase counterforce capabilities.

First, improved accuracy has transformed the role of ballistic missile submarines, turning these instruments of retaliation against population centers into potent counterforce weapons. Recall (from figure 3.1 above) that a 1985 submarine-launched ballistic missile (SLBM) had only a 9 percent chance of destroying a hardened target. This meant that although ballistic missile submarines could destroy "soft" targets (e.g., cities), they could not destroy the hardened sites that would be a key focus of a disarming attack. Increased SLBM accuracy has added hundreds of SLBM warheads to the counterforce arsenal; it has also unlocked other advantages that submarines possess over land-based missiles. For example, submarines have flexibility in firing location, allowing them to strike targets that are out of range of ICBMs or that are deployed in locations that ICBMs cannot hit.[25] Submarines also permit strikes from close range, reducing an adversary's response time. And because submarines can fire from unpredictable locations, SLBM launches are more difficult to detect than ICBM attacks, further reducing adversary response time before impact.

Second, upgraded fuses are making ballistic missiles even more capable than figure 3.1 reports. The new "burst-height compensating" fusing system, now deployed on all U.S. SLBM reentry vehicles, uses an altimeter to measure the difference between the actual and expected trajectory of the reentry vehicle, and then compensate for inaccuracies by adjusting the warhead's height of burst. Specifically, if the altimeter reveals that the warhead is off track and will detonate "short" of the target, the fusing system lowers the height of burst, allowing the weapon to travel farther (hence, closer to the aimpoint) before detonation. Alternatively, if the reentry vehicle is going to detonate beyond the target, the height of burst is automatically adjusted upward to allow the weapon to detonate before it travels too far. Without this technology, as figure 3.1 shows, the lower-yield W76 warheads are much less effective against hardened targets than their higher-yield cousins, the W88s. The improved fuse cuts the effectiveness gap roughly in half, making the hundreds of W76s in the U.S. arsenal potent counterforce weapons for the first time. The consequences of the fuse upgrades are, therefore, profound, essentially tripling the size of the U.S. submarine-based arsenal against hard targets.[26] More broadly, the technology at the core of compensating fuses is available to any state capable of building modern multistage ballistic missiles.[27]

A third key improvement, rapid missile reprogramming, increases the effectiveness of ballistic missiles by reducing the consequence of malfunctions. As figure 3.1 illustrates, when accuracy increases, missile reliability becomes the main hurdle to attacks on hardened targets. For decades, analysts have recognized a solution to this problem: if missile failures can be detected, the targets assigned to the malfunctioning missiles can be rapidly reassigned to other missiles held in reserve.[28] The capability to rapidly retarget missiles was installed at U.S. ICBM launch control centers in the 1990s and on U.S. submarines in the early 2000s, and both systems have since been upgraded.[29] We do not know if the United States has adopted war plans that fully exploit rapid reprogramming to minimize the effects of missile failures.[30] Nevertheless, such a targeting approach is within the technical capabilities of the United States and other major nuclear powers and may already be incorporated into war plans.[31]

Table 3.1 illustrates the consequences of these improvements against two hypothetical target sets: one hundred moderately hard mobile missile shelters and two hundred hardened missile silos.[32] Row 1 shows the approximate counterforce capabilities of a 1985-era U.S. Minuteman III ICBM strike; a two-on-one attack would have been expected to leave eight mobile missile shelters intact. A strike against two hundred hardened silos would fare worse, with forty-two targets expected to survive.

The remaining rows in table 3.1 highlight the implications of the changes that have occurred from 1985 to 2019. Row 2 illustrates the impact of improved Minuteman III guidance, which reportedly reduced circular error probable (CEP) from 183 to 120 meters. Row 3 employs the most capable missile and warhead combination in the current U.S. arsenal: the Trident II armed with a high-yield W88 warhead. As the results in both rows show, upgraded missiles perform better than their predecessor, but not well enough to conduct effective disarming strikes against large target sets.

Rows 4 to 7 demonstrate how the various improvements in missile technology have combined to create transformative counterforce capabilities. In row 4, we use a more realistic figure for missile system reliability. Although 80 percent missile reliability is traditionally used as a baseline, much evidence suggests that the actual reliability of modern missiles exceeds 90 percent. Row 4 shows attack outcomes for a Trident II/W88 with 90 percent reliability. Row 5 shows the consequences if the United States can reprogram its missiles to replace boost-phase failures. As row 5 reveals, a two-on-one attack with reprogramming would be expected to destroy every hardened shelter or silo. Row 6 omits reprogramming, but it demonstrates the impact of the decline in fratricide by adding a third warhead to each target, resulting again in the destruction of either target set.

Table 3.1. The demise of hard target survivability

			Weapon characteristics				*100 mobile missile shelters*		*200 hardened missile silos*	
	Description	*Weapon*	*Yield (kt)*	*CEP (m)*	*Reliability*	*Attack*	*p(K)*	*Survives*	*p(K)*	*Survives*
1	Baseline 1985	Minuteman W78	335	183	0.8	2:1	0.92	8	0.79	42
2	Baseline 2019	Minuteman W78	335	120	0.8	2:1	0.96	4	0.93	13
3		Trident II W88	455	90	0.8	2:1	0.96	4	0.96	8
4	Realistic reliability	Trident II W88	455	90	0.9	2:1	0.99	1	0.99	2
5	Reprogramming					2:1R	0.99+	0	0.99+	0
6	Many on 1					3:1	0.99+	0	0.99+	0
7	Compensating fuse	Trident II W76	100	90	0.9	2:1R	0.99+	0	0.99	1

Note: Results are displayed for 100 mobile missile shelters hardened to withstand up to 1,000 pounds per square inch (psi) or 200 missile silos hardened to 3,000 psi. Yield is in kilotons and circular error probable (CEP) is in meters. The category "Attack" indicates the number of warheads assigned to each target; "R" (for reprogramming) means that the attacker uses reserve missiles to replace boost phase malfunctions. The columns titled "p(K)" list the probability that each individual target is destroyed, and "Survives" is the expected number of targets surviving the attack. The designation of "0.99+" under p(K) indicates 99.9 percent or greater chance of destroying each individual target. Lightly shaded cells indicate successful disarming attacks; darker cells indicate very successful strikes. Note that a single surviving mobile missile shelter does not necessarily imply that a mobile missile survived, whereas a surviving silo suggests a surviving missile.

Row 7 illustrates the impact of compensating fuses. This row, unlike the others, employs the lower-yield warhead on the Trident II missiles (the W76). With the compensating fuse, a two-on-one attack using W76s would be expected to destroy all the mobile missile shelters and all but one of the hardened silos. (An attack that mixed W88s and W76s could destroy the entire hardened silo force.)

The results in table 3.1 are simply the output of a model. In the real world, the effectiveness of any strike would depend on many factors not modeled here, including the skill of the attacking forces, the accuracy of target intelligence, the ability of the targeted country to detect an inbound strike and "launch on warning," and other factors that depend on the political and strategic context. As a result, these calculations tell us less about the precise vulnerability of a given arsenal at a given time—though one can reach arresting conclusions based on the evidence—and more about trends in how technology is

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undermining survivability.

One crucial consequence of the accuracy revolution is not captured in the above results. Yet, its impact on the vulnerability of nuclear arsenals may be just as profound. The accuracy revolution has rendered low-casualty counterforce attacks plausible for the first time.

THE DAWN OF LOW-CASUALTY COUNTERFORCE

In nuclear deterrence theory, the primary factor preventing nuclear attack is the attacker's fear of retaliation. In reality, however, additional sources of inhibition exist, including the terrible civilian consequences of an attempted counterforce strike. If a leader contemplating a disarming strike knows that such an attack will inflict massive casualties on the enemy, that leader will also understand that the failure to disarm the enemy will provoke a massive punitive response, foreclosing the possibility of a limited nuclear exchange. Furthermore, if a disarming strike would cause enormous civilian casualties in the target country, but also possibly in allied and neutral neighboring countries, leaders who value human life or the fate of allies would contemplate such an attack in only the direst circumstances. The link between civilian casualties and nuclear inhibition explains why many arms control advocates oppose the development of less destructive nuclear weapons; they worry that such weapons are more “usable.”[35]

Counterforce was tantamount to mass casualties throughout the nuclear age, but the accuracy revolution is severing that link. In the past, the main impediment to low-casualty nuclear counterforce strikes has been radioactive fallout. Targeters would have had to rely on groundbursts to maximize destructive effects against hardened facilities such as silos and storage sites. Detonations close to the ground have a major drawback, however: debris is sucked up into the fireball, where it mixes with radioactive material, spreading radiation wherever it settles. Although the other effects of nuclear detonations (e.g., blast and fire) can have large-scale consequences for civilians, in many circumstances those effects can be minimized.[36] If a strike produces fallout, however, the consequences are potentially vast and difficult to predict.[37]

In theory, it has always been possible to employ nuclear weapons without creating much fallout. If weapons are detonated at high altitude (above the “fallout threshold”), very little debris from the ground will be drawn up into the fireball, greatly reducing fallout.[38] In practice, however, this targeting strategy has never been feasible against hardened sites. The problem is that any high-yield weapon that detonates low enough to destroy a hardened target will also be low enough to create fallout. Low-yield weapons could do the job and remain above the fallout threshold, but that has always been impractical because low-yield weapons would need to be delivered with great precision to destroy hardened sites, which was previously impossible.[39]

Figure 3.2 illustrates why high-yield strikes against hard targets inevitably create fallout, and it highlights the potential low-yield solution to the fallout problem. The vertical axis reflects weapon yield, and the horizontal axis depicts the hardness of potential targets—with the approximate values for mobile missile shelters and missile silos indicated. The solid black line shows the maximum yield of a weapon that can generate enough overpressure to destroy a target from above the fallout threshold. For example, figure 3.2 shows that for a 3,000 psi target, the highest-yield weapon that can destroy it while remaining above the fallout threshold is 0.35 kilotons. A larger-yield weapon will necessarily cause fallout if it destroys the target. A low-fallout strike against a 1,000 psi mobile missile shelter would require a weapon with 50 kilotons yield, or less. In short, low-fatality nuclear counterforce is possible, but it requires low-yield weapons, and hence very accurate delivery.

The accuracy of nuclear-delivery systems is now to the point that low-casualty disarming strikes are possible. For example, a 0.3 kiloton bomb would require a CEP of 10 to 15 meters to be highly effective against hard targets;[40] that level of accuracy is likely within the reach of the new guided B61-12, which is slated to replace all nuclear gravity bombs in the U.S. arsenal.[41] Similarly, a 5-kiloton missile warhead, which may approximate the yield of the fission primary on many existing ballistic missiles, could destroy a hardened target if its CEP was approximately 50 meters.[42] That level of accuracy was implausible for most of the Cold War, yet it is within reach of many countries today.[43]

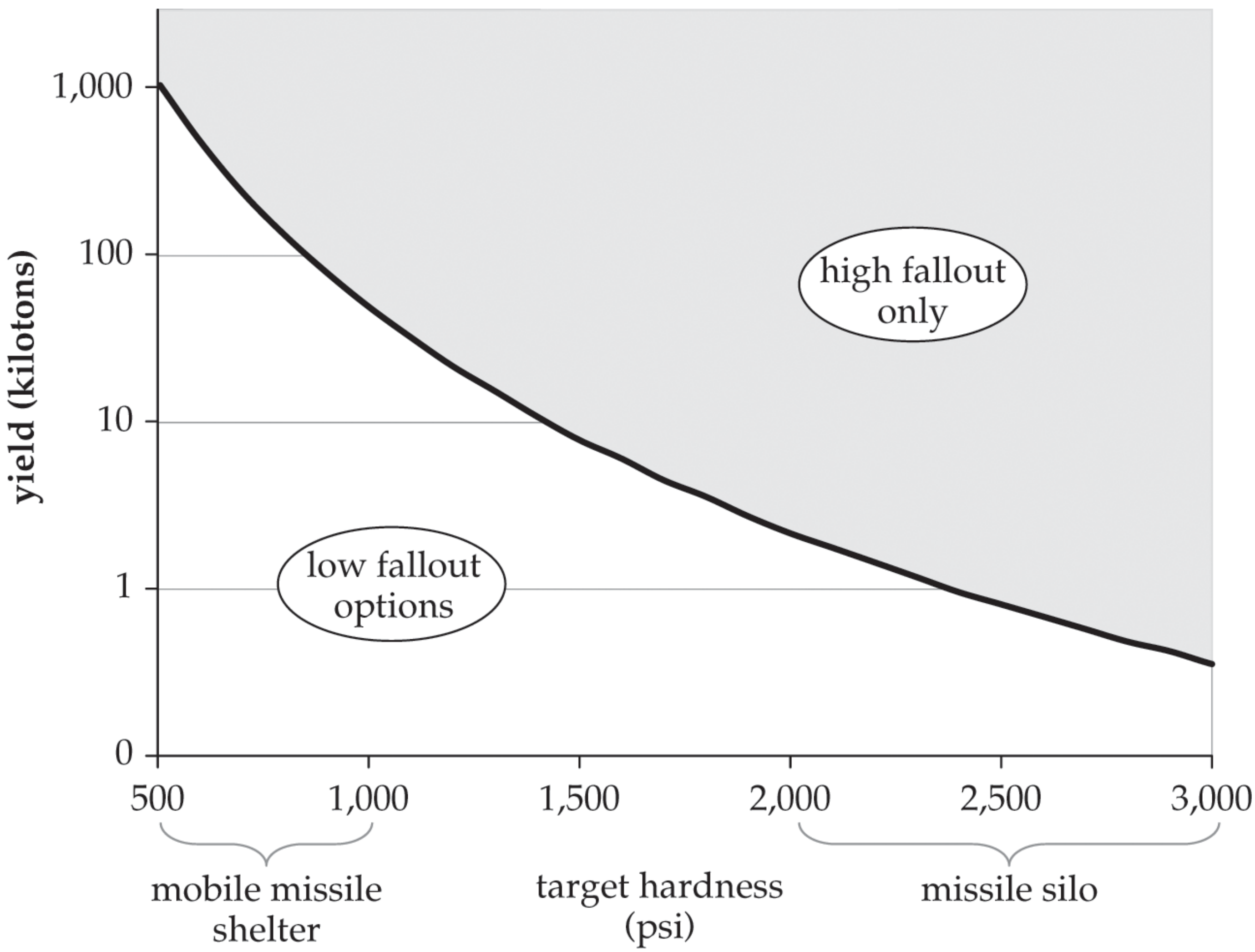

Figure 3.2. The potential for low-fallout nuclear counterforce

Note: "Target hardness" (the horizontal axis) is measured in pounds per square inch (psi), with a typical range of psi for hardened mobile missile shelters and missile silos noted. "Yield" (the vertical axis) is measured in kilotons and plotted on a logarithmic scale. The curve depicts the maximum weapon yield that can destroy a given target from above the fallout threshold. Any weapon yield/target hardness combination above the line that is effective enough to destroy the target will necessarily result in fallout. Points below the line indicate that weapons can be detonated at an altitude that will destroy the target yet produce little or no fallout.

By detonating weapons above the fallout threshold, targeters can greatly reduce fallout relative to groundbursts. But how significant are these reductions? How many fewer deaths would be caused in comparison with groundburst strikes?

To compare the fallout and potential fatalities from high-yield and low-yield counterforce operations, we used unclassified U.S. Defense Department software called Hazard Prediction and Assessment Capability (HPAC).[44] We modeled two different counterforce strikes, one using a "traditional" high-yield approach and one employing low-yield airbursts, against five hardened targets in North Korea (e.g., nuclear storage sites or hardened mobile missile shelters). Because there is no available unclassified information about the location of North Korea's nuclear storage sites, we modeled strikes against notional locations around the nation's periphery.

The results of the two strikes, illustrated in figure 3.3, are starkly different. The traditional approach (on the left side) would likely destroy the targets, but at a terrible price: millions of fatalities across the Korean Peninsula. The low-yield option, by contrast, would produce vastly fewer deaths. As long as the targets were located outside North Korean cities, the number of Korean fatalities from a low-yield strike would be comparable to the human losses from conventional operations. In fact, the fallout contours that are visible in figure 3.3 for the low-yield scenario correspond to annual radiation levels deemed acceptable by the U.S. Occupational Safety and Health Administration.

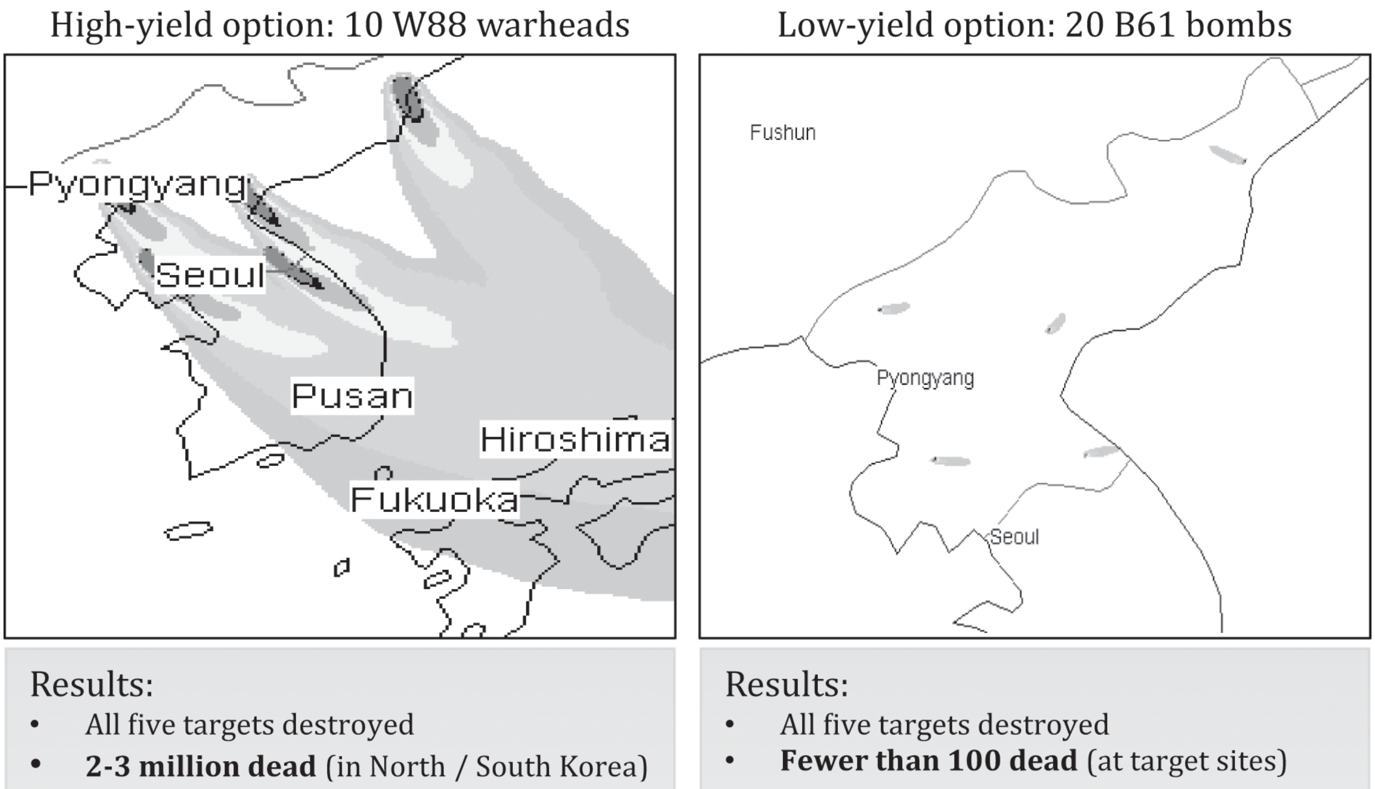

Figure 3.3. Low-fallout counterforce option against North Korea

Note: The figure illustrates the potential fallout consequences of two alternative counterforce strikes against five notional North Korean hardened nuclear sites. In both strike options each target is destroyed with greater than 95 percent probability. The high-yield attack employs 10 W-88 warheads (455-kiloton yield), with two warheads against each target. Because high-yield weapons cannot destroy hardened sites from above the fallout threshold, the W-88s are ground bursts. The low-yield attack uses 20 B-61 bombs (0.3-kiloton yield), set to detonate at an altitude that maximizes effectiveness while minimizing fallout. The fallout patterns and casualty figures were generated using unclassified U.S. Defense Department software, called Hazard Prediction and Assessment Capability.

The precise results of the HPAC simulation should be treated with skepticism, as wind speed and direction change constantly, altering fallout patterns. The amount of fallout generated in the low-yield scenario is so low, however, that the results of figure 3.3 are robust regardless of which way the wind blows; few people located away from the actual targets would be killed. The point of figure 3.3 is not to predict the outcome of a counterforce strike on North Korea but to reveal the relationship between accuracy and fallout. When accuracy was poor, the only approach to nuclear counterforce was high-yield strikes, which would create catastrophic results such as the one depicted above. The accuracy revolution has changed the [45] calculus, however; low-fatality nuclear strikes are now possible.

The accuracy revolution is ongoing. As accuracy continues to improve, the effectiveness of conventional attacks on hard targets will continue to increase. Today, low-yield nuclear weapons can destroy targets that once required very large-yield detonations. In the future, many of those targets will be vulnerable to conventional attacks.

In sum, from the start of the nuclear age to the present, force planners have relied on hardening as a key strategy for ensuring the survivability of their arsenals. That strategy made sense, and until recently it ensured that disarming strikes would not only fail but also kill millions of civilians in the process. Technology never stands still, however, and the technical foundations of deterrence, particularly for the strategy of hardening, have been greatly undermined by leaps in accuracy.

Counterforce in the Age of Transparency

While advances in accuracy are negating hardening as a strategy for protecting nuclear forces, improvements in remote sensing are undermining the other main approach: concealment. Finding concealed forces, particularly mobile ones, remains a major challenge. Trends in technology, however, are eroding the security that mobility once provided. In the ongoing competition between "hiders" and "seekers" waged by ballistic missile submarines, mobile land-based missiles, and the forces that seek to track them, the hider's job is growing more difficult than ever before.[46]

Five trends are ushering in an age of unprecedented transparency. First, sensor platforms have become more diverse. The mainstays of Cold War technical intelligence—satellites, submarines, and piloted aircraft—continue to play a vital role, and they are being supplemented by new platforms. For example, remotely piloted aircraft and underwater drones now gather intelligence during peacetime and war. Autonomous sensors, hidden on the ground or tethered to the seabed, monitor adversary facilities, forces, and operations. Additionally, the past two decades have witnessed the development of a new "virtual" sensing platform: cyberspying.[47]

Second, sensors are collecting a widening array of signals for analysis using a growing list of techniques. Early Cold War strategic intelligence relied heavily on photoreconnaissance, underwater acoustics, and the collection of adversary communications, all of which remain important. Now, modern sensors gather data from across the entire electromagnetic spectrum; they employ seismic and acoustic sensors in tandem; and they emit radar at various frequencies depending on their purpose—for example, to maximize resolution or to penetrate foliage. Modern remote sensing exploits an increasing number of analytic techniques, including spectroscopy to identify the vapors leaking from faraway facilities, interferometry to discover underground structures, and signals-processing techniques (such as those underpinning synthetic aperture radars) that allow radars to perform better than their antenna size would seem to permit.[48]

Third, remote-sensing platforms increasingly provide persistent observation. At the beginning of the Cold War, strategic intelligence was hobbled by sensors that collected snapshots rather than streams of data. Spy planes sprinted past targets, and satellites passed overhead and then disappeared over the horizon. Over time those sensors were supplemented with platforms that remained in place and soaked up data, such as signals-intelligence antennas, undersea hydrophones, and geostationary satellites. The trend toward persistence is continuing. Today, remotely piloted vehicles can loiter near enemy targets and autonomous sensors can monitor critical road junctures for months or years. Persistent observation is essential if the goal is not merely to count enemy weapons but also to track their movement.

The fourth factor in the ongoing remote sensing revolution is the steady improvement in sensor resolution. In every field that employs remote-sensing technology, including medicine, geology, and astronomy, improved sensors and advanced data processing are permitting more accurate measures and fainter signals to be discerned from background noise. The leap in satellite image resolution is but one example. The first U.S. reconnaissance satellite (Corona) could detect objects as small as 25 feet wide; today, commercial satellites (e.g., DigitalGlobe's WorldView-3 and WorldView-4) can collect images with 1-foot resolution and U.S. spy satellites are reportedly capable of resolutions of less than 4 inches.[49] Advances in resolution are not merely transforming optical remote-sensing systems; they are extending what can be seen by infrared sensors, advanced radars, interferometers and spectrographs, and many other sensors.

The fifth key trend is the huge increase in data transmission speed. During the first decades of the Cold War, it took days or longer to transmit information from sensors to analysts. At least a full day passed before the photographs snapped by U-2 aircraft were developed and analyzed. Early satellites were slower: the satellite had to finish its roll of film and then eject the canister, which would be caught midair and flown to a facility for development and analysis; all told, it might take weeks before images collected at the beginning of a satellite mission arrived at an analyst's desk. Today, by contrast, intelligence gathered by aircraft, satellites, and drones can be transmitted in nearly real time. The data can be transmitted to intelligence analysts, to political leaders, and in some cases directly to military commanders conducting operations.

None of these technological trends alone is transformative. Taken together, however, they are creating a degree of transparency that was unimaginable even two decades ago. These new remote-sensing technologies are not proliferating around the world evenly; the United States, for example, seems to have exploited new sensing technologies more intensively than other countries. Many countries are developing expertise in advanced sensing, however. The sensing revolution is a global phenomenon with implications for the survivability of all countries' nuclear arsenals.

Remote-sensing technologies have improved greatly, but the crucial question is whether these advances have meaningfully increased the vulnerability of the two most elusive types of nuclear-delivery systems: SSBNs and mobile land-based missiles. If the ability to track submarines at sea or mobile missiles on patrol remains out of reach, then the counterforce improvements we identify are less significant, at least for now. In fact, SSBNs have never been as invulnerable as analysts typically assume, and advances in remote sensing appear to be reducing the survivability of both submarines and mobile missiles.

REMOTE SENSING AND TRACKING SUBMARINES

During the Cold War, the competition between submariners and antisubmarine warfare operators was shrouded in secrecy, but that history is finally being revealed. We now know that the United States was able to locate and even track Soviet SSBNs during extended periods of the Cold War.[50]

The core of U.S. ASW efforts against the Soviet Union consisted of a series of breakthroughs in passive sonar and signals processing, as well as doctrine and tactics to exploit those advances. Starting in the 1950s, the United States deployed an expanding network of underwater hydrophones designed to identify and locate adversary submarines. Data from the hydrophones were transmitted across undersea cables to onshore computing facilities, where powerful computers discerned the faint sounds of submarines from ocean noise. Potential targets were then passed along to aircraft and attack submarines (SSNs) for further location and tracking. U.S. capabilities to track Soviet submarines leapt forward in the late 1960s and 1970s as the United States deployed new attack submarines that were equipped with powerful sonars in their bows, towed sonar arrays, and improved on-ship computing power, giving U.S. SSNs an unprecedented combination of acoustic-gathering and data-processing capabilities.[51]

The competition between Soviet SSBNs and the pack of U.S. submarines, aircraft, and surface ships hunting them varied throughout the Cold War. There were periods in which U.S. forces were winning, trailing every Soviet SSBN on patrol, from port to sea and back. Later, after discovering their vulnerability, the Russians pulled their forces into protected "bastions" near Soviet territory to counter the U.S. ASW strategy. The United States did not give up, and worked until the end of the Cold War (and beyond) to regain undersea superiority.

The duration of U.S. Cold War ASW superiority cannot be accurately assessed today because of enduring classification constraints. But for periods of the superpower competition, U.S. naval leaders believed they had the ASW problem well in hand. As the former commander of the U.S. Pacific Fleet in the mid-1980s remarked, the United States was able to "identify by hull number the identity of Soviet subs … and know exactly where they were. In port or at sea. If they were at sea, N3 [director for operations] had an SSN [on them]."[52]

There are three key lessons to draw from the Cold War ASW competition. First, previous advances in remote sensing greatly increased the vulnerability of deployed submarines.[53] Second, escaping vulnerability was no easy task. In the late 1960s, the Soviet Union learned that its submarines were vulnerable. But despite Moscow's significant economic and technological resources, it took the Soviet navy more than a decade to develop good countermeasures against the evolving U.S. ASW capabilities.[54]

Third, and most broadly, the Cold War ASW competition demonstrates that the deployment of ballistic missile submarines neither ended the Cold War nuclear competition nor negated hopes on either side of attaining military superiority. The United States led the undersea competition for a time because of its superior technology and tactics; the Soviet Union developed countermeasures because it discovered its vulnerabilities and innovated. This back-and-forth struggle between hiders and seekers looks more like a traditional struggle for naval superiority than the common depiction of invulnerable submarines.

Today's technological advances in remote sensing, data processing, and communication are occurring at a rapid pace, and their ultimate impact on the submarine competition is too uncertain to predict with confidence (especially given the tight controls over information on contemporary ASW capabilities). Yet, there are good reasons to suspect that the dramatic leaps in remote sensing are increasing the transparency of the seas and undermining the ability of submarines to remain concealed. Some of the promising new antisubmarine technologies include improved acoustic sensors (including low-frequency active sonars and new networks of seabed passive sonars); nonacoustic techniques (using lasers, magnetometers, and satellites); sophisticated "big data" analysis (which exploits leaps in processor speed to sift vast quantities of sensor data); and a variety of unmanned and autonomous underwater vehicles (including those designed to find and shadow adversary submarines for weeks or months).[55]

The point is not that submarines are now easy to locate or that the challenges of ASW have been solved. Locating technologically sophisticated, well-operated submarines in vast ocean sanctuaries remains a substantial challenge. Rather, the key point is that even the nuclear-delivery system sometimes touted as the most survivable has been vulnerable in the past and appears to be increasingly vulnerable today, as ASW efforts and capabilities rapidly improve. What about mobile land-based missiles? Are breakthroughs in sensing technology increasing their vulnerability as well?

REMOTE SENSING AND HUNTING MOBILE MISSILES

We illustrate the impact of two advanced surveillance systems, radar satellites and remotely piloted aircraft, on the survivability of mobile land-based nuclear missiles. The effectiveness of sensing systems depends on the characteristics of the target country—for example, its size, location, topography, and defenses. As such, their impact is difficult to quantify in the abstract. Instead, we explore the potential contributions of two advanced sensor systems in a hypothetical case: a U.S.-led operation to destroy a small arsenal of North Korean nuclear-tipped mobile missiles.[56] We assume that North Korea's TELs are postured like most other countries' mobile missiles—they remain in hardened shelters during peacetime, with plans to disperse a portion of the force during a conflict.[57]

U.S. and allied strategic intelligence would have at least three critical roles in support of a military operation against North Korean TELs. The first, a peacetime mission called *intelligence preparation of the battlefield* (IPB), involves locating North Korea's nuclear and missile facilities, identifying the patrol routes utilized by its missile forces, learning its organizational routines, and mapping its command and communication network. The other two roles are principally wartime missions. *Detection* refers to sensing possible targets; it typically involves sensors that can monitor large areas but have inadequate resolution for positive identification or targeting. *Identification* is the next step; once a possible target is detected, other platforms (often with higher-resolution sensors) are cued to identify and precisely locate the target.[58]

A core element of U.S. surveillance capabilities is the constellation of satellites that use synthetic aperture radar (SAR) to image targets on the ground. Satellites provide a unique capability to peer deep into adversary territory, and they are especially useful for missions that require frequent observations of critical facilities. Whereas manned aircraft and unmanned aerial vehicles (UAVs) are often restricted from adversary airspace, satellites routinely overfly adversary territory. Moreover, unlike satellites with optical or infrared sensors, radar satellites can image targets at night and through cloudy weather.

Until recently, the type of radar employed on most satellites—SAR—could not image moving targets, which limited the effectiveness of space-based sensors for hunting mobile missiles.[59] But over the past two decades, engineers have developed data-processing techniques that enable SAR systems to detect moving targets and determine their speed and direction of travel.[60]

Although the precise capabilities of intelligence satellites are classified, civilian radar satellites can scan approximately 150-kilometer-wide swaths along the ground as they pass overhead, with sufficient resolution to detect truck-sized moving vehicles.[61] New techniques are being developed that may soon double or triple the width of the swath that can be scanned on each pass.[62]

SAR-equipped satellites, now able to find mobile targets, have the potential to transform counter-TEL operations. If U.S. intelligence satellites can detect moving vehicles within a 150-kilometer-wide swath along the ground—a conservative assumption, given that a civilian satellite launched nearly a decade ago can do so—then centering the radar on a mobile missile garrison would put all the roads within two hours' drive time of that facility within the radar's swath width.[63] A single satellite can generate up to twelve 150-by-150-kilometer swaths in a single pass over North Korea, enough to image all the country's roads more than once—and key sections multiple times—before passing over the horizon.[64]

Although SAR satellites have become powerful tools for hunting TELs, they have important limitations. Surveillance satellites provide only intermittent coverage of key areas, passing overhead and then descending over the horizon. Thus, even if a constellation of satellites could image the entire road network in North Korea every hour, North Korean TELs might be able to disperse without being observed, by seeking shelter whenever a satellite approaches. Furthermore, if many of North Korea's critical facilities are located in its mountainous regions, topography may block the satellite's line of sight, which would allow targets within the swath to be hidden from the radar. The potential effectiveness of radar satellites for hunting mobile missiles, therefore, depends on two key factors: the time interval between satellite passes and the percentage of road network that is observable in a given pass.[65]

To assess the effectiveness of SAR satellites for hunting North Korean mobile missiles, we conducted an analysis with three key steps. First, we created a digital map of North Korea's roads. Second, we used geospatial analysis software to determine the visible portion of those roads as a function of a satellite's position. Third, we calculated the frequency with which satellites

[66]

pass within an orbital band that provides high levels of visibility of the road network.

Our analysis of satellite orbits and North Korean topography reveals that satellites passing through an orbital band that stretches as far as a 1,500-kilometer lateral distance from the Korean Peninsula can view, on average, 90 percent of North Korean roads. A typical radar satellite (which operates in low earth orbit) will pass through such a band—what we call a "usable pass"—roughly 2.5 times per day. The total number of usable passes per day thus depends on the number of SAR satellites in orbit that are available for hunting mobile missiles. The number of available satellites, in turn, depends on the willingness of the United States and its close allies to share sensitive satellite imagery, the technical preparations that have been undertaken to facilitate that sharing, and the precise technical capabilities of the satellites. Table 3.2 shows the implications of different assumptions about those uncertainties. If the United States and key allies create the political and technical arrangements to share satellite data during wartime, North Korean TEL commanders would have little time between passes—specifically, as few as twenty-four minutes.[67]

Table 3.2. Synthetic aperture radar (SAR) satellites and frequency of usable passes

	Number of SAR satellites	*Available satellites*	*Usable passes per day*	*Minutes between usable passes*
United States	6	6	15	91
Other NATO	9	15	37	34
Japan	3	18	44	27
Israel	2	20	50	24

Note: The column "Number of SAR satellites" counts major military and intelligence SAR satellites operated by the United States and key allies. The other columns are cumulative and show how satellite coverage grows when one adds the assets of various U.S. partners. "Usable passes per day" indicates the daily satellite over flights that pass through an orbital band that offers, on average, 90 percent coverage of North Korean roads.

Twenty-four minutes between satellite passes could provide enough time for TELs or other vehicles to move quickly from shelter to shelter, but that strategy requires precise information on satellite orbits, and the short time interval between passes leaves little margin for error for vehicles racing for cover. Moreover, the challenge for TEL operators is more serious than the data suggest. The analysis here focuses on the twenty military and intelligence SAR satellites, not the half dozen or more U.S. and allied civilian platforms that might be pressed into service in wartime.[68] Nor does the analysis count the optical and infrared satellites that supplement SAR coverage. Finally, the number and capability of radar satellites available to the United States is growing.[69] As that number increases, the window for mobile missiles to scoot away without being observed will narrow further.

SAR satellites do not solve the problem of locating mobile targets. For one thing, Russia and China are improving their ASAT capabilities, partly in response to U.S. capabilities.[70] Furthermore, adversaries will seek to place missile garrisons and conduct deterrent patrols in locations that are difficult to observe.[71] Those choices, however, force adversaries into ever-narrower zones, which then become the focus of other surveillance tools—for example, stealthy penetrating UAVs and unattended ground sensors.

In terms of the three key sensing missions (IPB, detection, and identification), SAR-equipped satellites offer a high level of capability for the IPB mission, because they can repeatedly image stationary or moving targets in peacetime. They also contribute a high level of capability to detection, by offering frequent wide-area coverage of North Korean roads. Finally, SAR satellites offer fairly good capability for the identification mission; they can produce high-resolution images of stationary TELs and enough resolution of moving vehicles to determine that a target is "truck-sized."[72]

A second set of sensing capabilities lies in a fleet of aircraft, including manned and remotely piloted vehicles, that use powerful radars to scan adversary territory. These aircraft carry SARs, and many are equipped with ground moving target indicator (GMTI) radars, allowing them to create high-resolution images of stationary targets or track a large number of moving vehicles. Most surveillance aircraft must operate from "standoff" distances to reduce their vulnerability to air defenses. Some drones, however, are stealthy and can penetrate adversary airspace. Below we illustrate the capabilities of standoff SAR/GMTI platforms and penetrating UAVs in the context of a U.S. and allied operation against North Korean mobile missiles.

The United States uses several types of aircraft for standoff radar-reconnaissance missions; we base our model on one of them, the remotely piloted RQ-4 Global Hawk. We explore the potential effectiveness of radar surveillance from four continuous orbits 80 kilometers outside North Korean territory.[73] ArcGIS software allows us to identify orbital locations that maximize coverage of North Korean roads, as well as to calculate the visible percentage of the road network from those locations.[74] Figure 3.4 shows the results.

Figure 3.4 reveals that even against a small country such as North Korea, standoff airborne radars cannot, by themselves, provide complete coverage of key roads and regions. Four orbits can observe 54 percent of North Korea's roads; the remainder is out of sensor range or shielded by mountainous terrain. These results also suggest, however, that standoff UAVs could play a crucial role in a sensing operation; that is, the ability to continuously monitor roughly half of North Korea's road network during a conflict would compel North Korea to constrain its mobile missile operations to the north-central region of the peninsula.[75]

In addition to standoff UAVs, the United States has developed drones for so-called penetrating operations. These UAVs reduce their visibility to enemy radar by utilizing stealth technologies and a combination of passive sensors and "low-probability of intercept" (LPI) radars to observe targets on the ground.[76]

Even sophisticated, stealthy UAVs are vulnerable to air defenses. To some extent their vulnerability depends on technical issues, including the state of competition between radar engineers and designers of stealth technology. The vulnerability of penetrating drones, however, depends greatly on their mission. Of the two critical wartime missions, detection is likely more dangerous than identification. The detection mission—continuously monitoring a large area to detect possible targets—would require a drone to remain within the line of sight of a large portion of adversary territory. The mission would, therefore, require the drone to fly at high altitude (to maximize line of sight) and possibly use active sensors (to maximize the drone's sensor range). The identification mission, on the other hand, would allow penetrating drones to protect themselves better—to operate at lower altitude so that terrain would shield them from enemy sensors, and fly (when cued by detection systems) to investigate a possible TEL. Only then would the penetrating UAV employ LPI or passive sensors to examine the potential target.

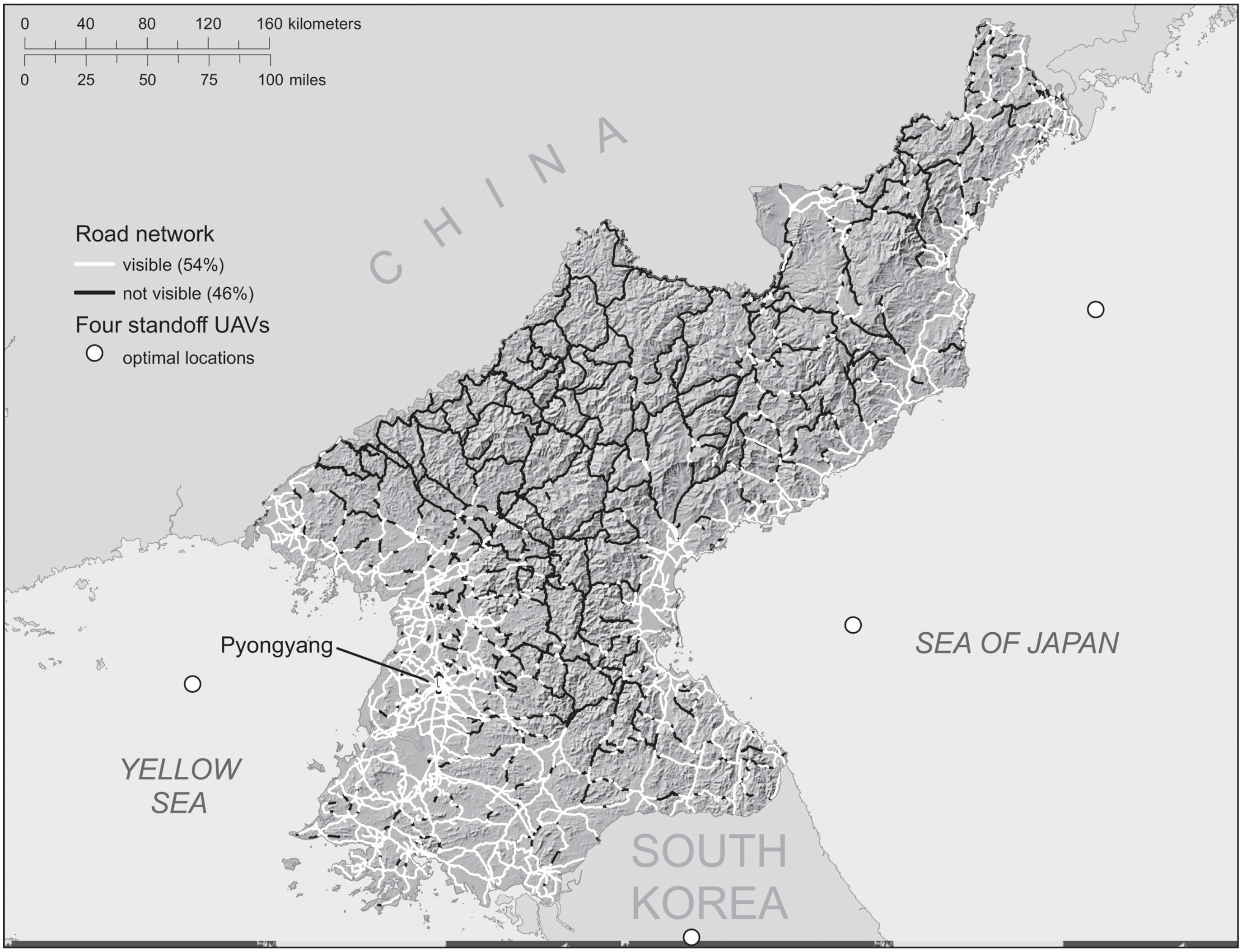

Figure 3.4. Coverage of North Korea with standoff unmanned aerial vehicles (UAVs)

Note: The white circles depict potential orbital locations for four UAVs; the locations were selected to maximize surveillance of North Korea's road network. The orbits are located 80 kilometers from North Korea's territory at an altitude of 60,000 feet, which reflect plausible operations for RQ-4 Global Hawks. White road segments are observable from at least one of the locations. The image was created using ArcGIS and road data from OpenStreetMap and DIVA-GIS.

We used ArcGIS to explore the potential capability of penetrating drones in the identification mission by determining the percentage of the North Korean road network that would be visible using four UAV orbits. Because the penetrating UAVs would need to rapidly identify the vehicles detected by other sensors, we restricted the UAVs to five minutes of flight time to maneuver into position to observe the suspected TEL.[77] Furthermore, because LPI radars and passive sensors have shorter ranges than the powerful radars on standoff platforms, we limit the sensor range to 50 kilometers.[78]

Our analysis reveals that four penetrating drones, operating as we describe above, can identify targets along 84 percent of North Korea's roads.[79] As figure 3.5 shows, penetrating and standoff systems would be particularly effective in combination, increasing the road network coverage to 97 percent. Assuming that penetrating UAVs can be cued by other reconnaissance systems such as satellites, unattended ground sensors, or (near the coast) standoff drones, North Korean TEL operators would have great difficulty moving safely along the country's road network without being detected. If U.S. and South Korean intelligence had identified mobile missile garrisons and operating areas before the conflict, the regions surrounding those zones might be fully covered by only one or two drone orbits.[80]

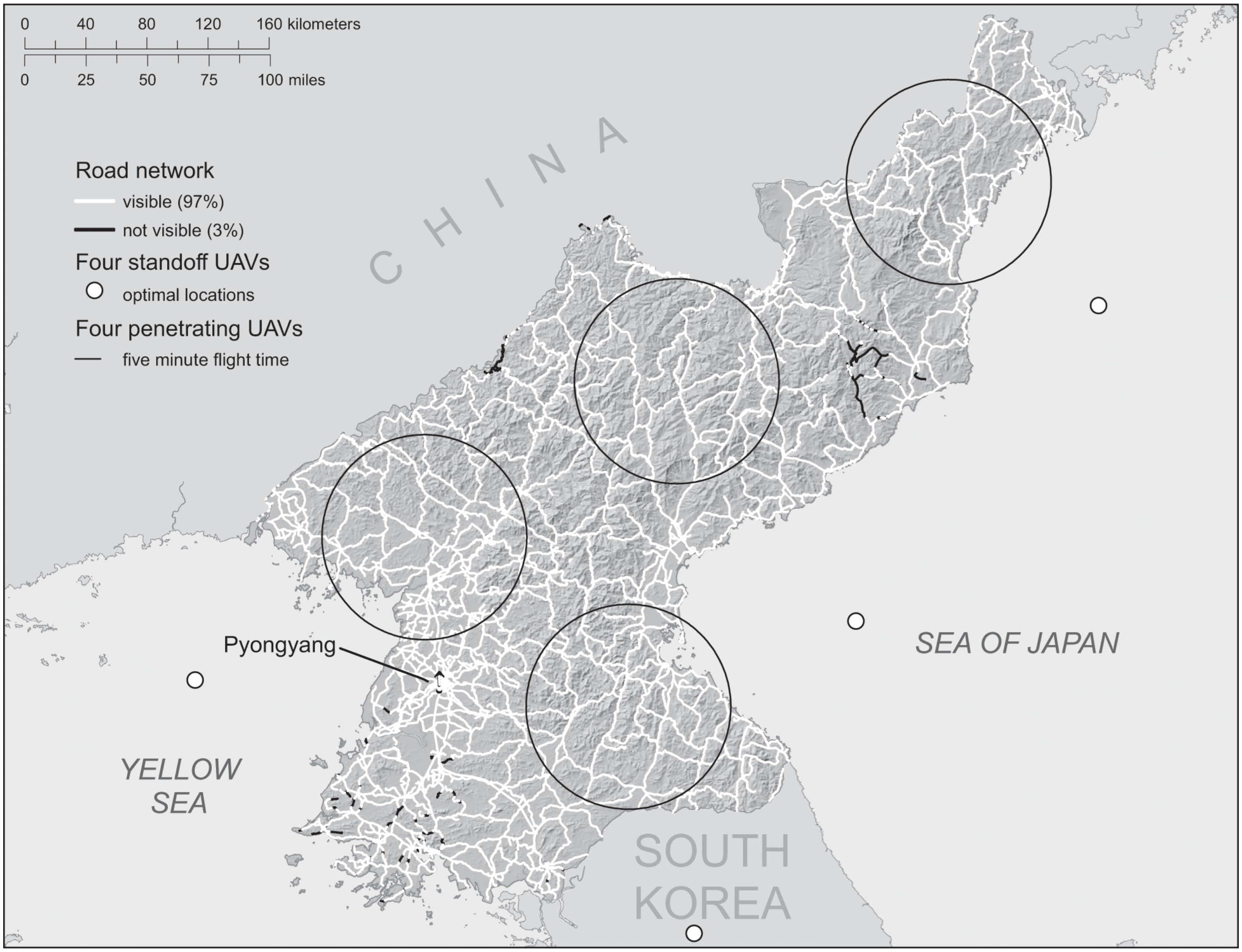

Figure 3.5. Coverage of North Korea with standoff and penetrating unmanned aerial vehicles

Note: The white circles depict potential orbital locations for four UAVs operating 80 kilometers outside North Korea's territory. The black circles depict the area over North Korea that four penetrating UAVs can overfly within five minutes of flight time starting from the center of each circle. Road segments are coded as visible (white) if they are observable from either a standoff or penetrating UAV. The image was created using ArcGIS and road data from OpenStreetMap and DIVA-GIS.

Each of the sensing systems explored here has important limitations. For example, radar satellites provide wide-area coverage, but do so intermittently and at only moderate resolution. Standoff drones provide persistent coverage, but only near the coast. Penetrating drones can provide persistent coverage inland (at the cost of increased risk to the aircraft) or intermittent inland coverage at lower risk. In many cases, however, the capabilities of one system can offset the limits of another. Moreover, this analysis merely scratches the surface in terms of new sensing platforms (e.g., unattended ground and seabed systems), signals (e.g., high-resolution spectroscopy), and approaches (e.g., cyber intrusions), many of which would be employed together for the same mission.

Old assumptions about the survivability of mobile forces need to be revised in light of new sensing technologies and capabilities. Concealment is not impossible, of course. An adversary's mobile delivery systems can remain secure if its air defenses can keep UAVs at bay, its navy can keep enemy ASW forces from its coastal waters, and antisatellite technology can blind satellites. But in this new era of transparency, whether concealed forces are survivable or not depends on the state of competition between opposing intelligence and military organizations. Survivability through concealment can no longer be assumed.

What about Countermeasures?

Countries will surely address the growing vulnerability of their nuclear arsenals by trying to develop countermeasures to thwart advanced sensor and strike systems. They will seek to deploy radar jammers, antisatellite weapons, and decoys. They will try to adapt mobile missile doctrines to reduce vulnerability, by timing movements to elude satellites and minimizing communications to thwart signals-intelligence efforts, for example. The new era of counterforce will not be static; it will be characterized by vigorous efforts to develop countermeasures, as well as equally vigorous efforts to overcome them.

Yet, there are good reasons to expect that the net result of these efforts will leave nuclear-delivery systems more vulnerable than they have been in the recent past. First, hunters are poised to do well in the back-and-forth battle of countermeasures. Counterforce is the domain of the powerful; those that are seeking to track enemy nuclear forces typically have greater resources than their rivals.[81] Additionally, the countries that are leaders in sensing technology have an advantage in the race to build (and thwart) countermeasures. As Brendan Green and Austin Long observe about the Cold War ASW competition, U.S. superiority in passive acoustics helped the United States quiet its own SSBNs, which in turn allowed it to practice and hone its tracking capabilities.[82] Expertise in sensors and countermeasures go hand in hand. Perhaps most importantly, many countermeasures reduce one vulnerability at the cost of exacerbating others. For example, limiting communications between mobile missiles or submarines and their command authorities reduces vulnerability to signals intercepts, but it increases vulnerability to attacks designed to sever (or simulate) their command and control.[83] Avoiding coastal roads neutralizes offshore sensors, but it channels forces into a smaller zone, easing the search problem. Even the simplest countermeasures, such as increasing security near sensitive facilities to prevent the emplacement of unattended ground sensors or improving air defenses around key sites to thwart UAVs, may cue hunters to the presence of high-value sites.

Second, the potential targets of disarming strikes cannot respond to just a single counterforce technology; they must respond to a daunting list of them. The revolutions in accuracy and sensing have had multiple, synergistic effects in bolstering counterforce. The task for hiders is not simply to thwart a single platform, such as SAR satellites, but rather to develop countermeasures to the entire array of (known) capabilities deployed by the hunters. For example, North Korea may find ways to interfere with U.S. radar satellites, but that still leaves missiles vulnerable to detection by optical satellites, UAVs, unattended ground sensors, and a variety of tagging, tracking, and locating capabilities.

Third, some vulnerabilities are difficult to fix. In the late 1960s, the Soviet Union learned that its SSBNs were being tracked by the United States, but it took more than a decade to counter this U.S. capability. Consider the challenge faced by China today in building a survivable ballistic missile submarine force. China deployed its first submarines in the 1960s, but more than half a century later Chinese submarines are still so noisy that experts predict it will be decades before Beijing can field survivable submarines.[84]

Finally, although the impact of emerging technologies on nuclear command, control, and communications (NC3) and early warning (EW) systems is difficult to predict, there are good reasons to expect that this will be an area of growing vulnerability for countries facing sophisticated adversaries. Nuclear retaliation, after all, depends on surviving NC3 capabilities (and in some cases, effective EW), not just the survival of warheads and delivery systems. During the Cold War, the Soviet Union was notably deficient in some aspects of NC3, increasing Soviet vulnerability to electronic warfare, stealthy aircraft and cruise missiles, and electromagnetic pulse (EMP) effects.[85] Today, all nuclear-armed countries need to be concerned that advances in quantum computing, artificial intelligence, and cyber could undermine the ability to detect a nuclear first strike or order and deliver a retaliatory response.

The battle between countermeasures and corresponding attempts to defeat them is under way, and its outcome will likely depend on the strategic context. Rich countries with advanced research and development infrastructure are developing technology and doctrine to protect their nuclear forces in the face of improvements in weapons accuracy and remote sensing. Weaker countries with modest resources, however, will be hard-pressed to develop effective countermeasures to the full spectrum of emerging means of counterforce.

For most of the nuclear age, there were many impediments to effective counterforce. Weapons were too inaccurate to reliably destroy hardened targets; fratricide prevented many-on-one targeting; the number of targets to strike was huge; target intelligence was poor; conventional weapons were of limited use; and any attempt at disarming an adversary would be expected to kill vast numbers of people. Today, in stark contrast, highly accurate weapons aim at shrinking enemy target sets. The fratricide problem has been swept away. Conventional weapons can destroy most types of counterforce targets, and low-fatality nuclear strikes can be employed against others. Target intelligence, especially against mobile targets, remains the biggest obstacle to effective counterforce, but the technological changes under way in that domain are revolutionary. Of the two key strategies that countries have employed since the start of the nuclear age to keep their arsenals safe, hardening has been negated, and concealment is under great duress.

These developments help explain the enduring puzzle of the nuclear age. Nuclear weapons seem like the ultimate instruments of deterrence, protecting those who possess them from invasion and other major attacks. Yet, if nuclear weapons solve countries' most fundamental security problems, why do nuclear-armed countries continue to perceive serious threats from abroad and engage in intense security competition? Why have the great powers of the nuclear era behaved in many ways like their predecessors from previous centuries, by building alliances, engaging in arms races, competing for relative gains, and seeking to control strategic territory—none of which should matter much if nuclear weapons guarantee the nation's security?

One might blame this persistent discrepancy between nuclear theory and practice on misguided leadership, bureaucratic or other decision-making pathologies, or dysfunctional domestic politics. The new era of counterforce suggests, however, that leaders have been correct to perceive that stalemate can be broken, and that the nuclear balance can vary dramatically across cases. If today's secure arsenal can become tomorrow's first-strike target, then there is little reason to expect the geopolitical competition between countries to end with the deployment of seemingly secure nuclear weapons.

The policy implications of the new era of counterforce are also important. First, if nuclear forces are becoming increasingly vulnerable to counterforce, then states need to improve their retaliatory arsenals just to maintain the same level of deterrence. Given that nuclear-delivery systems are expensive and must last for decades, the challenge for force planners is extraordinary: deploy weapon systems that will remain survivable for multiple generations, even as technology improves at an ever-increasing pace.

Second, the growing threat to nuclear arsenals (from nuclear strikes, conventional attacks, missile defenses, ASW, and cyber operations) raises major questions about the wisdom of cutting the size of nuclear arsenals. In the past, many arms control advocates believed that arms cuts reduced the incentives for disarming strikes; whether that assumption was right or wrong at the time, it is increasingly dubious as a recipe for deterrence stability today.

Finally, leaps in accuracy and remote sensing should reopen debates in the United States about the wisdom of pursuing effective counterforce systems. Fielding those capabilities—nuclear, conventional, and other—may prove invaluable, enhancing deterrence during conventional wars and, if deterrence fails, allowing the United States to defend itself and its allies.[86]

Enhancing counterforce capabilities, however, may trigger arms races and other dynamics that exacerbate political and military conditions.[87] In the past, technological conditions bolstered those who favored restraint; disarming strikes seemed impossible, so enhancing counterforce would likely trigger arms racing without much strategic benefit. Today, technological trends appear to validate the advocates of counterforce. Remote sensing, conventional strike capabilities, ASW, and cyberattack techniques will continue to improve and increasingly threaten strategic forces whether or not the United States seeks to maximize its counterforce capabilities. In this new era of counterforce, technological arms racing seems inevitable, so exercising restraint may limit options without yielding much benefit.

Nuclear deterrence can be robust, but nothing about it has ever been automatic or everlasting. U.S. leaders sought the capabilities to escape stalemate in the Cold War competition with the Soviet Union, and the United States remains in the vanguard of countries pursuing counterforce today. Stalemate might endure among some nuclear countries, and technology could someday reestablish the ease of deploying survivable arsenals. Today, however, survivability is eroding, and it will continue to do so in the foreseeable future. Weapons will grow even more accurate. Sensors will improve. The new era of counterforce will likely yield benefits to those countries that best adapt to the new landscape, and costs to those that fall behind. This familiar competitive dynamic explains why power politics endure in the nuclear age.