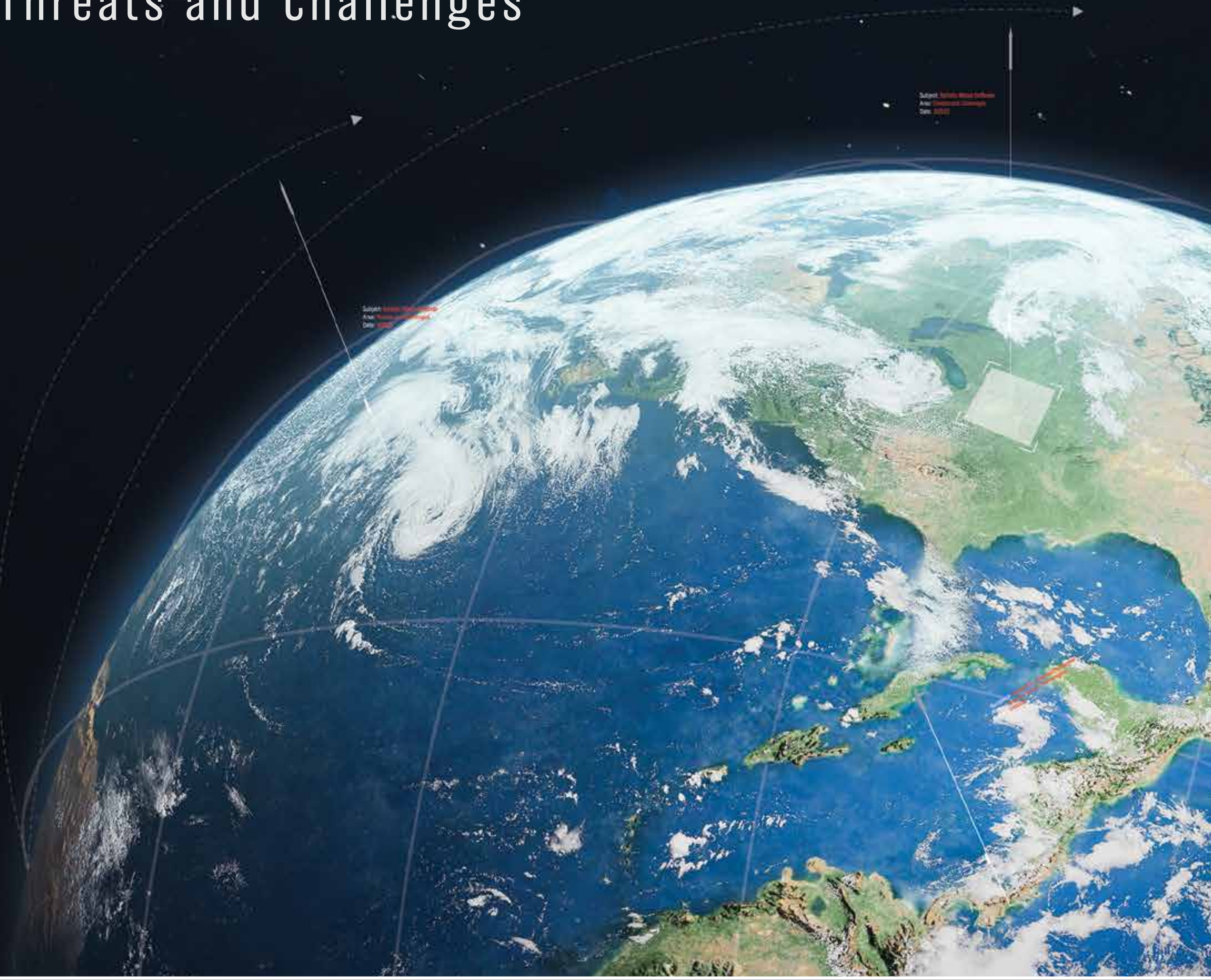
BALLISTIC MISSILE DEFENSE

Threats and Challenges



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**Dr. Coyle passed away as the study was ending.*

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The American Physical Society has sole responsibility for the contents of this report, and the questions, findings, and recommendations within.

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1. INTRODUCTION

One of the most critical security challenges for humankind is the existence of nuclear weapons. Nuclear-armed intercontinental ballistic missiles (ICBMs) exacerbate this challenge by making people vulnerable to sudden nuclear attack—whether deliberate or mistaken—from across the globe. The explosion of even a single nuclear warhead over a major U.S. city would be an enormous disaster, potentially killing a million people and reducing 100 square miles to rubble [DOD 1977]. Multiple large nuclear explosions over cities would be a catastrophe for all humanity (see [OTA 1979] and the discussion of climatic effects in [NRC 1985]).

A natural reaction to such a threat is to consider the possibilities for intercepting and disabling nuclear-armed ICBMs before they reach their targets. The United States has been pursuing the possibility of a defense against ballistic missiles for over 65 years. Missile defense efforts have so far cost American taxpayers over $350 billion in 2020 dollars [BMD Expenditures 2021], most of which has been for intercepting ICBMs. However, as we explain below, no missile defense system thus far developed has been shown to be effective against realistic ICBM threats.

From 1972 to 2002, the Anti-Ballistic Missile (ABM) Treaty permitted the United States and the Soviet Union (later Russia) to deploy only limited defenses against ICBMs, defined as ballistic missiles with ranges greater than 5,500 km. Then the National Missile Defense Act of 1999 restricted the United States to deploying only a system that could defend against a limited ballistic missile attack, which was understood to mean an attack using the smaller number of less sophisticated missiles that a country such as North Korea, Iran, or Iraq might have, or a small accidental or unauthorized launch by China or Russia [NMDA 1999]. Today, Iraq and Iran have no nuclear weapons, although there is concern that Iran might develop them in the future. North Korea, which has tested both nuclear weapons and ICBMs capable of delivering them [CRS 2021a; Kristensen 2021], has therefore become a primary focus of the current U.S. ballistic missile defense (BMD) program.

In 2002, the United States withdrew from the U.S.-Russian ABM Treaty, which had been designed to prevent missile defense efforts from driving defense-offense arms race cycles between the two countries. Then, in 2016, the U.S. Congress struck the word "limited" from its description of the threat the U.S. BMD program is charged with defending against [NDAA 2017, Sec. 1681], thereby opening the door to pursuing defenses against Russian and Chinese ICBMs. Russia and China also have missile defense programs [Baklitskiy 2021], although they currently have little strategic relevance to the United States.

An unusual aspect of any effort to defend against nuclear-armed ICBMs in flight is that it provides decisive protection only once it is nearly perfect, because a successful attack by even one nuclear-armed ICBM would be catastrophic, but its negative strategic and arms race implications are felt immediately. We recognize that a limited missile defense capability may be perceived as having value for deterring an attack on the United States or its allies, facilitating a preventive war or a pre-emptive attack by the United States, limiting the damage caused by a nuclear attack in case of war, increasing the bargaining power of the United States vis-à-vis North Korea, China, and Russia, or for other purposes. All these considerations must be factored into national policy but are outside the scope of the present brief study.

In this report, we focus on questions that are narrow enough to be answered with some confidence but have broad implications for programs and systems whose goal is to defend against ICBMs in flight. In particular, we focus on the fundamental question of whether current and proposed systems intended to defend the United States against nuclear-armed ICBMs are now effective, or could in the near future be made effective in preventing the death and destruction that a successful attack by North Korea on the United States using such ICBMs would produce. As noted above, this is a primary concern of the current U.S. missile defense program. In addressing this question, we consider ICBMs that North Korea might have within the 15-year horizon of this study. However, we do not consider multiple, maneuvering, or glider-like ICBM warheads. Although North Korea has tested maneuvering warheads and a glider-like warhead on medium-range missiles and is seeking to develop the capability to launch multiple nuclear warheads on a single missile, it has not yet demonstrated these technologies on an ICBM. As we discuss in this report, building a practical, effective defense against North Korean ICBMs that do not take advantage of any of these technologies is already extremely challenging. We do not discuss North Korea's short-, medium-, and intermediate-range missiles, which would chiefly be used in the Asia-Pacific region.

We also do not consider missile defense systems intended to defend against the numerically larger and technically more sophisticated current and future nuclear-armed ICBM forces of Russia or China. These forces are likely to include delivery systems that use technologies specifically designed to defeat current and future U.S. defenses against ballistic missiles, such as maneuvering warheads, multiple independently targeted warheads, and hypersonic glide weapons. They may also include delivery systems designed to circumvent current and future U.S. defenses against ballistic missiles, such as short-range ballistic missiles launched from ships off U.S. coasts, nuclear weapons launched on fractional-orbit trajectories (sometimes referred to as fractional orbital bombardment systems or FOBS), nuclear-armed uncrewed underwater vehicles, or nuclear-armed cruise missiles. Defending against these more numerous and sophisticated threats is likely to be much more challenging than defending against the numerically smaller and technologically less sophisticated threat posed by the nuclear-armed North Korean ICBM force that we focus on here.

A key purpose of this report is to explain why a defense against even the limited ICBM threat we consider is so technically challenging, and where the many technical difficulties lie. Our hope is that readers will come away with realistic views of the current capabilities of U.S. systems intended to defend against the nuclear-armed ICBMs North Korea may have at present and an improved understanding of the prospects for being able to defend against the ICBMs North Korea might deploy within the next 15 years. In our view, despite some high-profile comments to the contrary [Panetta 2012; Trump 2019; Hyten 2020], the current capabilities are low and will likely continue to be low for the next 15 years.

To focus our report further, we consider what would be required to defend against the launch of a single ICBM from North Korea, or the salvo launch of 10 in rapid succession, taking into account countermeasures North Korea may be able to use to penetrate U.S.

defensive systems. While these are only two of many possible attacks, considering them reveals many of the technical challenges and broader implications of any effort to defend against nuclear-armed ICBMs.

Figure 1 illustrates three ICBM trajectories from North Korea to the United States. The distance to Boston is about 11,000 km and an ICBM would travel this distance in about 40 minutes.

In general, defense against an ICBM can be attempted during any of its three phases of flight:

- ***Boost phase.*** During its boost phase, the ICBM's rocket engines are burning, producing a bright exhaust plume as it lifts off and gains altitude and speed. This phase lasts three to five minutes for current ICBMs, depending on their design.
- ***Midcourse phase.*** The midcourse phase begins when the engine of the missile's final stage has stopped burning. At that point the rocket body's final stage, one or more warheads, and any other objects that have been discarded or deployed by the missile—such as deployment modules, insulation, and other parts of the booster, or deliberate countermeasures to the defensive system—begin moving along ballistic trajectories in space. This phase lasts approximately 30 to 40 minutes for ICBM trajectories from North Korea to the continental United States.
- ***Terminal phase.*** The terminal phase begins once the warhead(s) and accompanying objects re-enter the atmosphere at an altitude of about 100 km, slowing due to air resistance as the warhead descends toward its target. This phase lasts less than a minute.

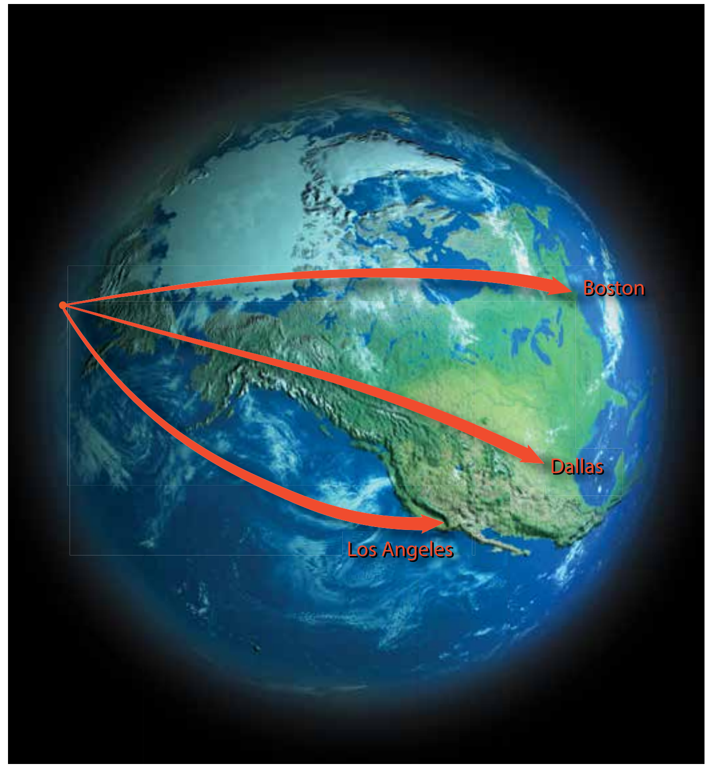


Figure 1 View of Earth illustrating the trajectories of ICBMs from North Korea to Los Angeles, Dallas, and Boston. The trajectories shown are great circles rather than the true trajectories, which would need to take into account the rotation of Earth.

The objective of a missile defense system is to disable the ICBM or its warhead during one of these three phases of flight.

The weapons currently being proposed to disable North Korean ICBMs during their boost phase are airborne or space-based rocket interceptors. The proposed airborne interceptors would be based on long-duration, heavy-payload uncrewed aerial vehicles ("drones") or aircraft positioned near or even over North Korea, China, or Russia, close to the initial flight paths of North Korean ICBMs potentially heading toward the United States.

The current U.S. midcourse intercept systems are the Ground-based Midcourse Defense (GMD), which currently has interceptors

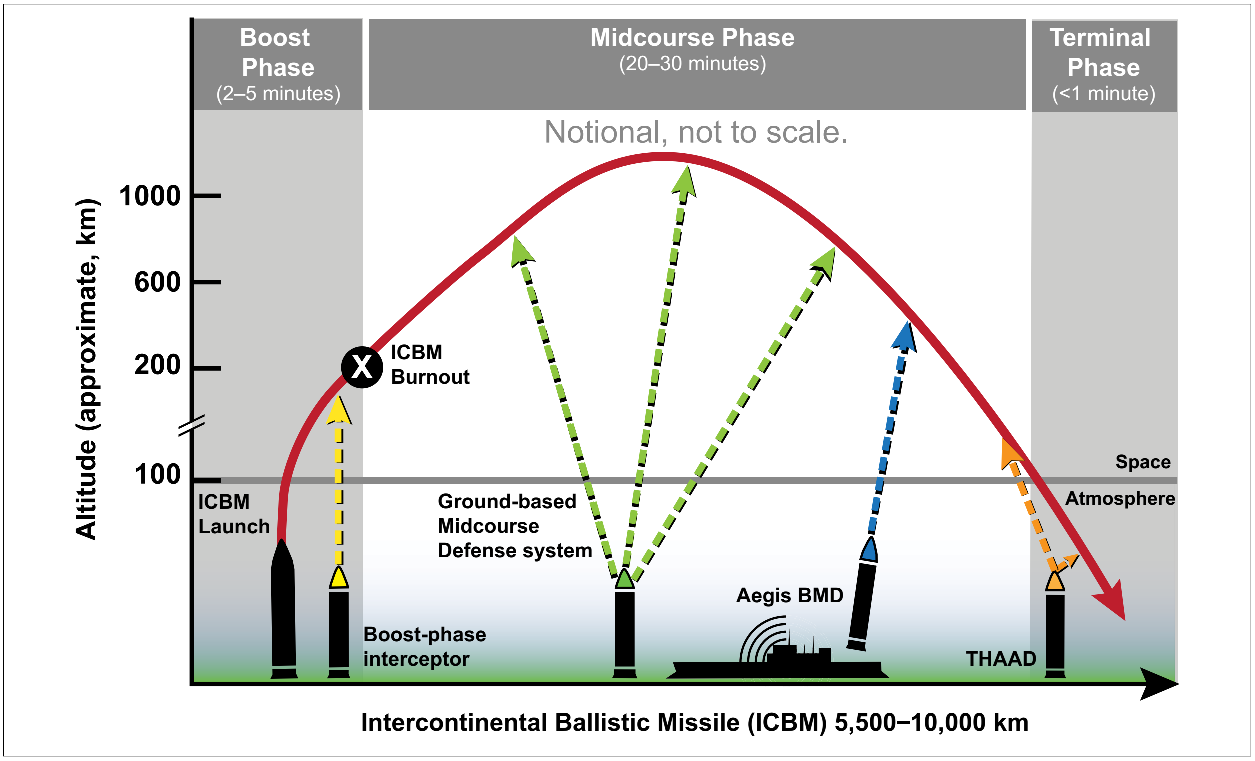


Figure 2 Schematic portrayal of the layered missile defense system being proposed to defend the United States against ICBMs launched from North Korea. An attempt can be made to intercept an ICBM while its rocket engine is burning (its boost phase), during the flight of its warhead through the vacuum of space (the midcourse phase), or after its warhead has re-entered the sensible atmosphere (the terminal phase). Currently, the sole system deployed to defend the U.S. homeland from an intercontinental ballistic missile attack is the Ground-based Midcourse Defense (GMD) system. To increase the overall effectiveness of the system, in 2020 the Missile Defense Agency proposed the layered system depicted here, in which intercept attempts by the GMD system would be followed by intercept attempts by the Aegis regional midcourse defense system, and perhaps finally by a terminal defense system based on an enhancement of the existing THAAD system. No boost-phase intercept system currently exists. (Note that the vertical scale changes at the break in the axis shown on the left.)

deployed at Fort Greely, Alaska, and Vandenberg Air Force Base, California, and the Aegis BMD system, which is currently being used to defend U.S. military installations and allied territory but is now being proposed as an additional midcourse intercept system to protect U.S. territory.

The very short duration of the terminal phase requires terminal interceptors to be deployed very close to the area they are intended to defend. The Army's transportable Terminal High-Altitude Area Defense (THAAD) was developed to defend against the warheads of shorter-range ballistic missiles, but there are now proposals to upgrade it to attempt the much more challenging task of defending against much faster ICBM warheads.

Figure 2 presents a pictorial overview of these deployed and proposed system elements. We discuss these elements in more detail below.

The most recent U.S. Missile Defense Review [MDR 2019] calls for further development and testing of all the missile defense elements mentioned above and more; $10 billion or more has been allocated annually to this program in recent years. While this could change as the current administration reviews its nuclear and missile defense postures, current executive branch and congressional guidance and budget allocations largely continue the direction of the existing program.

Although this report is primarily technical, it does discuss some of the wider implications of missile defenses, such as their likely effects on the current U.S. offensive-defensive nuclear competition with North Korea, China, and Russia. These effects include the incentives the deployment of defenses gives Russia and China to develop and deploy additional nuclear-armed ICBMs and other, new offensive weapons as hedges against future breakthroughs in U.S. missile defense capabilities [Baklitskiy 2021; Cropsey 2021; Erästö 2021; for a different perspective, see Roberts 2014; Roberts 2020]. These developments appear to be generating a new nuclear arms race to deploy more, and more sophisticated, offensive and defensive weapons.

We do not consider many other important questions related to missile defenses, such as the appropriate level of funding for missile defense relative to other priorities.

Both U.S. government and nongovernmental experts have assessed that a primary motivation for North Korea's nuclear weapons and missile programs is to deter other countries from attempting to change North Korea's ruling regime by force [DOD 2020a; Bennett 2021; CRS 2021a]. According to the October 2021 report by the U.S. Defense Intelligence Agency (DIA), "North Korea's perception that the outside world is inherently hostile drives the North's security strategy and pursuit of specific military developments. This perception is informed by a history of invasion and subjugation by stronger powers stretching back centuries and, in the 20th century, by the 1910–45 Japanese occupation and the externally enforced division of the Korean Peninsula at the end of World War II" [DIA 2021]. The DIA report assesses that the primary motivations that led Kim Jong Il to put the North on a path to a nuclear breakout in the mid-2000s were "apprehension about U.S. military intentions after the 9/11 attacks and major [U.S.] operations in Afghanistan and Iraq, a continually worsening military imbalance on the [Korean] peninsula, and failure to obtain anticipated energy assistance and other economic concessions from international negotiations." It concludes that the objectives of North Korea's military are "to hold the United States at bay while preserving the capacity to inflict sufficient damage on the South, such that both countries have no choice but to respect the North's sovereignty and treat it as an equal."

These assessments and conclusions suggest that reducing the threat of North Korea's ICBMs requires careful analysis and responses to all relevant dimensions of this problem, including its political and diplomatic aspects as well as its military dimensions. Ballistic missile defense capabilities are just one component of this complex question.

The next two sections describe North Korea's current and possible near-term ICBMs and nuclear warheads, and some of the key challenges that confront efforts to build a system that could defend against them once they are launched. The two main sections of the report then follow. The first describes midcourse intercept systems, including the GMD system and potential contributions of the regional Aegis BMD and THAAD systems, while the second describes boost-phase intercept systems, including possible land-, sea-, air-, and space-based rocket interceptors and aircraft-based missiles and laser weapons. The report ends with some closing thoughts.

2. NORTH KOREA'S ICBM CAPABILITIES

This report considers the threat posed to the United States by North Korea's potential deployment of a limited but significant number of nuclear-armed ICBMs within the 15-year time horizon of this study. Focusing on this threat is consistent with previous U.S. missile defense policies and the 2019 Missile Defense Review [MDR 2019], which stated (p. IX) that U.S. missile defense capabilities are sized to defend the U.S. homeland against the limited offensive missile threats posed by states such as North Korea. It is also consistent with the assessment (see below) that North Korea is unlikely to deploy intercontinental-range submarine-based ballistic missiles that could strike the U.S. homeland within the time horizon of this study. The United States relies on nuclear deterrence to deter attacks from any source, including North Korea [MDR 2019, IX].

In contrast to North Korea, Iran does not have nuclear weapons or ICBMs and is currently observing a self-imposed moratorium on testing ballistic missiles with ranges greater than 2,000 km [Einhorn 2019]. While Iran likely could produce a nuclear weapon and an ICBM within the 15-year time horizon of this study [Belk 2018; Cordesman 2019; Einhorn 2019; Elleman 2021a], we do not explicitly consider this possibility. However, much of our discussion would be relevant to assessing the potential for the United States to defend itself against nuclear-armed Iranian ICBMs.

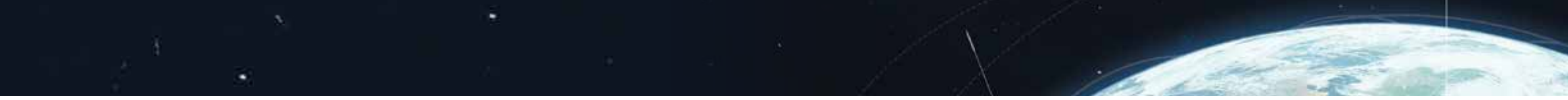
We also do not discuss the capabilities of missile defense systems to defend against the ICBM or submarine-launched ballistic missile (SLBM) forces of Russia or China. This is consistent with previous U.S. missile defense policies and the 2019 Missile Defense Review [MDR 2019], which states (p. 8), "The United States relies on nuclear deterrence to prevent potential Russian or Chinese nuclear attacks employing their large and technically sophisticated intercontinental missile systems," and with the fiscal year 2020 (FY20) National Defense Authorization Act [NDAA 2020], which says (Sec. 1681), "It is the policy of the United States to rely on nuclear deterrence to address more sophisticated and larger quantity near-peer intercontinental ballistic missile threats."

North Korea's long-range ballistic missiles

Liquid-propellant ICBMs. North Korea has successfully tested two types of liquid-propellant ICBMs capable of striking part or all of the continental United States. It tested its first ICBM, the Hwasong-14 (U.S. designation KN-20), on July 4 and July 28, 2017 [CSIS 2021]. This missile is estimated to have a full burn time of about 375 seconds and a range of more than 10,000 km [CSIS 2021; DIA 2021, 24].

North Korea tested a longer-range ICBM, the Hwasong-15 (KN-22), on November 28, 2017. This missile is estimated to have a full burn time of 290 seconds, a maximum range of about 13,000 km [Panda 2017; Dominguez 2019; Bennett 2021; CSIS 2021; DIA 2021, 24], and the ability to carry "penetration aids" (devices designed to enable the warheads to penetrate defensive systems). It shares some design features with the early Soviet UR-100/SS-11 missile and has an engine based on the Soviet RD-250, but its engine uses two gimbaled main chambers for steering, rather than four small vernier engines. Changes such as these suggest modest indigenous North Korean missile engineering ability [Schiller 2019].

In its October 2020 military parade, North Korea displayed a model of a new liquid-pro-



pellant ICBM, the Hwasong-16 (KN-27), which is much larger than previous North Korean ICBMs [Hansen 2020; Van Diepen 2020; Varner 2020]. A functioning missile of this size would be able to carry multiple warheads and penetration aids.

Solid-propellant ICBMs. Boost-phase defense against solid-propellant ICBMs is more challenging because they can be launched with less preparation time and have substantially shorter burn times than liquid-propellant ICBMs. North Korea has not yet built or tested a solid-propellant ICBM, but it does have a solid-propellant missile development program [Smith 2020].

North Korea successfully tested a medium-range solid-propellant ballistic missile, the Pukkŭksŏng-1 (KN-11), with a range of more than 1,000 km, in August 2016 [CSIS 2021; DIA 2021, 24]. This missile was presented as intended to be launched from a submarine. North Korea has developed additional missiles in this series, including the Pukkŭksŏng-2 (KN-15) [Elleman 2017; CSIS 2021], Pukkŭksŏng-3 (KN-26) [CSIS 2021], and possibly a Pukkŭksŏng-4 [Van Diepen 2020; Varner 2020]. In January 2021, North Korea displayed a model of a new, larger, solid-propellant missile, the Pukkŭksŏng-5 (KN-15), which appears similar in size and shape to the U.S. Polaris A3 SLBM [Elleman 2021b]. It continues to test these solid-propellant missiles, with the most recent test occurring on October 18, 2021 [Choe 2021b]. Although advertised as SLBMs, these missiles could also be launched from land.

The Pukkŭksŏng missiles are estimated to have ranges of 1,000 - 2,000 km [CSIS 2021]. To produce a solid-propellant ballistic missile with intercontinental range, North Korea would have to develop significantly larger solid rocket motors. Based on the history of the U.S. [Caveny 2003] and Soviet [Podvig 2004] ICBM programs, some of the technical challenges involved in scaling up solid rocket motors to the sizes required may already have been overcome by North Korea in producing its current motors, but other challenges would need to be surmounted to produce motors large enough for ICBMs [Schiller 2019].

It appears unlikely that North Korea can develop and deploy solid-propellant SLBMs with intercontinental ranges and the submarines needed to carry and launch them within the 15-year time horizon of this study [Kim 2021a; Kim 2021c]. However, it might be able to develop and deploy a solid-propellant ICBM, depending on the foreign assistance it receives and whether its current solid rocket motors are being manufactured within North Korea or elsewhere [Smith 2020].

Launch platforms for long-range ballistic missiles. In recent congressional testimony, Gen. Scott Berrier, Director of the Defense Intelligence Agency, noted [Berrier 2021], "The October 2020 parade also featured eight road-mobile ICBM launchers, the most North Korea has ever displayed." This suggests that North Korea's ability to deploy ICBMs may no longer be constrained by its apparent former inability to produce adequate transporter-erector-launchers, and that it may now be able to deploy 10 or more ICBMs on mobile launchers.

North Korea is also working to develop the ability to launch missiles from trains [Van Diepen 2021a; Smith 2021], which if successful could allow it to launch heavier missiles such as ICBMs from a larger number and a wider range of locations.

Finally, North Korea is continuing its program to develop small, diesel-powered submarines that could carry and launch up to three Pukkŭksŏng ballistic missiles [Sutton 2019; Cha 2020; Nikkei 2021]. However, these submarines are vulnerable because they are slow, cannot remain submerged for long periods, and have relatively loud acoustic signatures [Kim 2021a]. Consequently, we do not consider them further in this report.

North Korea's nuclear weapons

North Korea apparently already had a nuclear weapons program and had fabricated two or three nuclear devices by the late 1990s (see [Kristensen 2021] for a detailed review of what is known and surmised about North Korea's nuclear weapons program). It has so far tested six nuclear devices, two with yields estimated to be in the range of 10 to 15 kilotons and one with a much larger yield estimated to be in the range of 140 to 250 kilotons. Due to the opacity of North Korea's nuclear program, U.S. and international officials, experts, and agencies have had difficulty assessing the program's purposes and accomplishments.

Knowledgeable observers estimate that North Korea might have produced enough fissile material (plutonium and highly enriched uranium) to construct 20 to 60 nuclear weapons but may have assembled fewer [DOD 2020a; CRS 2021a; Hecker 2021; Kristensen 2021]. Most of these weapons would likely be single-stage fission weapons with possible yields of 10 to 20 kilotons with at most only a few thermonuclear weapons [Kristensen 2021]. Some have estimated that North Korea may be able to produce enough fissile material to construct about 3 to 7 additional weapons per year [DOD 2020a; CRS 2021a; Kristensen 2021]. If so, North Korea could produce enough fissile material to make 50 to 100 additional nuclear weapons within the 15-year time horizon of this study.

Missile warheads and penetration aids

Nuclear warheads for ICBMs. North Korea is likely to have already developed, or could develop soon, a nuclear weapon small and light enough to be carried by the Hwasong-15 and a re-entry vehicle robust enough to survive the rigors of launch and re-entry into the atmosphere after a full-range ICBM flight. Two reports requested by the U.S. government assessed that as of 2017 North Korea had developed a nuclear warhead that could be mounted on its ICBMs [Bennett 2021; CRS 2021a]. A careful independent assessment [Wright 2017] concluded that "North Korea has not yet demonstrated a working re-entry vehicle (RV) on a trajectory that its missiles would fly if used against the United States. However, there doesn't appear to be a technical barrier to building a working RV, and doing so is not likely to be a significant challenge compared to what North Korea has already accomplished in its missile program. … While the United States put very significant resources into developing sophisticated RVs and heatshields … that effort was to develop highly accurate missiles and is not indicative of the effort required by North Korea to develop an adequate RV to deliver a nuclear weapon to a city."

Countermeasures to missile defenses. In 1999, the U.S. national intelligence community assessed that Russia and China have both developed numerous countermeasures to missile defense and probably are willing to sell the requisite technologies, and that emerging missile states such as North Korea would likely have developed countermeasures by the time they flight-test their missiles [NIC 1999].

For some years, North Korea has been developing technologies designed to give its warheads greater ability to penetrate missile defense systems. At least two of the short-range missiles it introduced in 2019, the KN-23 and KN-24, are reported to have warheads that can perform low-altitude maneuvers, making them harder to intercept [Choe 2021a]. In October 2021, North Korea test-launched what it called its first hypersonic missile, the Hwasong-8, which appears to have a boost-glide warhead [Choe 2021a; Gallo 2021; Panda 2021;Trevithick 2021]. In an official statement, the South Korean Joint Chiefs of Staff said that this missile "appears to be at an early stage of development that would require considerable time for actual deployment" [Choi 2021; see also Van Diepen 2021b]. In January 2022, North Korea launched two different, apparently improved hypersonic boost-glide vehicles that could be advanced MaRVs [Rogoway 2022; Smith 2022]. We assess that North Korea has devoted substantial efforts to developing countermeasures to missile defenses and is continuing to do so.

North Korean ICBM capability we consider

Based on the information just described, North Korea probably has a few liquid-propellant ICBMs that could strike the continental United States and may be able to deploy 10 or more within the 15-year time horizon of this study. Publicly available information indicates that it probably has transporter-erector-launchers for these missiles and is working on being able to launch large missiles from trains. North Korea is developing solid-propellant missiles and might be able to develop and deploy a few solid-propellant ICBMs within 15 years. The reliability of these long-range missiles has not been demonstrated.

North Korea has probably assembled several nuclear weapons and may have several dozen within the 15-year time horizon of this study. According to the assessments cited above, most are probably fission devices with yields in the 10 - 15 kiloton range, but a few may be thermonuclear weapons with yields of about 200 kilotons. Numerous sources assess that North Korea has developed nuclear devices small enough to be launched by its ICBMs and, given the assessments cited above, will have enough nuclear weapons to mount them on its ICBMs. North Korea has not yet demonstrated a working re-entry vehicle on a trajectory its missiles would fly if used against the United States, but there appears to be no technical barrier to its building them. The accuracy of these missiles is likely to be low, and they would therefore probably be used against relatively large targets, such as cities, rather than against hardened military targets.

The U.S. intelligence community has assessed that North Korea has likely developed countermeasures to missile defenses. It is equipping its shorter-range missiles with maneuvering re-entry vehicles and is actively working on more advanced countermeasures, such as a possible glider-like warhead. It has not yet demonstrated these countermeasures in tests of long-range missiles.

Based on these assessments of North Korea's current nuclear-armed ICBM capabilities and those it may be able to develop within the 15-year time horizon of this report, the following chapters focus on the performance that a missile defense system would need to have to successfully defend the continental United States against the baseline threat represented by the launch of a single liquid-propellant ICBM like the Hwasong-15 or a salvo launch of 10 such ICBMs at intervals of less than a minute. Although it would be challenging for North Korea to deploy solid-propellant ICBMs within the 15-year time horizon of this study, it might do so, and the consequences for any boost-phase defense system would be profound. We therefore consider this possibility in our report. As we show, the missile defense systems that would be needed to defend against these threats are technically very challenging and illustrate the difficulty of providing decisive protection against even limited threats.

3. CHALLENGES OF MISSILE DEFENSE

Intercepting even a single nuclear-armed intercontinental-range ballistic missile or its warhead(s) in flight under the conditions expected during a nuclear attack is extremely challenging. The ability of any missile defense system to do this reliably has not been demonstrated.

Here we briefly mention some of the important challenges faced by any program to develop and deploy an effective missile defense system. These include technical challenges and challenges created by the adversary's ability to respond to defensive measures. We also call attention to the difficulties encountered in using the results of independent evaluations effectively to remedy problems identified in this large and complex defense program.

Technical challenges. The argument is sometimes made that missile defense must be feasible because of the reputed successes of Israel's "Iron Dome" system and the U.S. Patriot system. But the challenges faced by these systems are far less than those confronting any system attempting to defend against ICBMs. Moreover, neither the Iron Dome system nor the Patriot system is fully successful against the much-less-capable missiles it is designed to defend against.

The Iron Dome system was developed about a decade ago to defend against rockets, artillery, mortar shells, and simple, very short-range, highly inaccurate home-made rockets that travel at speeds of only about 1 km/s over distances of only about 7 - 70 km and carry warheads with an explosive power of about 10 kg of TNT [Bartels 2017; Hambling 2021]. Iron Dome interceptors have an effective range of 4 - 70 km [Lister 2021]. They do not strike the incoming missiles but instead try to approach them and then explode, sending out shrapnel that can disable the home-made rockets if the interceptor is approaching the rocket from the right direction and gets close enough [Postol 2014]. The Iron Dome system has been greatly improved over the decade it has been in use. It now engages about 50% of the rockets launched against the area it is defending and is claimed to destroy about 80% - 90% of the rockets it engages [Bartels 2017; Hambling 2021; Lister 2021].

The U.S. Patriot system was originally designed to defend against aircraft, but at the outset of the 1991 Gulf War it was rushed to the Gulf to try to defend the Israeli population and U.S. military forces against attacks by Iraq's Al-Hussein missiles, a variant of the Scud missile with a range of about 600 km. But the Patriot system almost completely failed to do this. A subsequent investigation by the House Committee on Government Operations found, "There is little evidence to prove that the Patriot hit more than a few Scud missiles launched by Iraq during the Gulf War" and added, "There are some doubts about even these engagements" [Congress 1992]. (For further details, see [Lewis 1993; Sullivan 1999].)

More recently, the United States supplied Patriot Advanced Capability-3 systems to Saudi Arabia to help it defend against missiles launched by Houthi forces. On November 4, 2017, Houthis attacked the airport in the Saudi capital, Riyadh, using a Burqan-2 [Williams 2020], a variant of the Scud with a reported range of about 1,000 km [Savelsberg 2018]. According to evidence collected during and after the attack, the relevant Patriot defensive battery fired five interceptors at the missile, but its warhead flew unimpeded over the interceptors and detonated on Riyadh's airport, indicating that the defense failed when confronting a missile much less capable than an ICBM [Fisher 2017].

The interceptors of Israel's Iron Dome system and the interceptors of the U.S. Patriot system are both designed to explode near the warheads of missiles traveling within the atmosphere, and these systems therefore cannot be fooled by lightweight decoys. In contrast, U.S. GMD interceptors must strike directly the warheads of ICBMs while they are traveling far above the atmosphere, where the GMD system could be fooled by lightweight decoys and other penetration aids (see below). Moreover, the warheads the GMD system would have to engage would be traversing distances of 12,000 km or more at speeds of more than 7 km/s, distances 100 times greater and speeds seven times faster than the missiles engaged by Israel's Iron Dome, and distances 10 times greater and speeds more than two times faster than the warhead the Patriot system missed. If the GMD system misses the nuclear warhead it is seeking to destroy, the warhead could explode on its target with a power a million times greater than the warheads that the Iron Dome and Patriot systems sometimes miss, utterly destroying its target and the surrounding area.

For systems intended to defend against ICBMs, the brevity of the boost and re-entry phases of these missiles and the lack of air resistance during the midcourse phase pose severe technical challenges for the defense. Moreover, "to be credible and effective, a ballistic missile defense system must be robust even if any of its elements fail to work as planned" (see [NRC 2012], Major Finding 6, S-9).

The boost phases of current ICBMs last three to five minutes, depending on their design. Hence, as will be explained in the boost-phase intercept section, for a land-, sea-, or air-based interceptor rocket to intercept an ICBM during its boost phase, the interceptor must typically be based within about 500 km of the intended intercept point, have a speed of 5 km/s or more, and be fired less than a minute after the launch of a potentially threatening missile has been detected. Interceptor bases and aircraft must be positioned 100 to 200 km from the borders of potentially hostile countries, or, in the case of sea-based interceptors, at least 100 km from the coasts of potentially hostile countries, so that the ships that are carrying the interceptors are beyond the horizons of land-based radars and have adequate room for maneuvering (see [APS 2003, S66]). As discussed below, these requirements severely restrict the ability of a system of land-, sea-, or air-based rockets to intercept an ICBM during its boost phase. If a large enough number of rocket interceptors were instead placed in appropriate low-Earth orbits, a sufficient number would be within range of any attacking ICBM during its boost phase to attempt an intercept. But as discussed below, a constellation of many hundreds of interceptors in low-Earth orbit would be required for one to be within range at all times to defend against even a single ICBM launched from a single site. As also discussed below, there are a variety of potentially effective countermeasures against boost-phase intercept, such as launching several ICBMs nearly simultaneously (a "salvo launch") or programming evasive maneuvers by the ICBM.

The midcourse phase, during which nuclear warheads follow ballistic trajectories, lasts about 30 to 40 minutes, but the absence of air drag during this phase means that launch debris, such as spent upper stages, deployment modules or attitude control modules, separation debris, debris from unburned fuel, insulation, and other parts of the booster, as well as deliberately generated missile fragments, lightweight decoys, and other penetration aids, will all follow the same trajectory as a warhead. This makes it difficult for the defense to discriminate the warhead from other objects in this "threat cloud," so that it can target the warhead. The radar and infrared sensors required for tracking, discrimination, and homing are vulnerable to the effects of high-altitude nuclear detonations, which may be preplanned or result from a successful intercept.

The terminal phase, during which the nuclear warhead re-enters the atmosphere, lasts only about a minute. As a result, only very high-speed rocket interceptors launched from bases close to the warhead's target could reach and destroy a warhead during the terminal phase of its flight before it detonates. Furthermore, lightweight decoys would be stripped away by the atmosphere only during the final 10 seconds or so before the warhead explodes. Terminal-phase defenses can therefore potentially defend only limited areas, such as a metropolitan area or a critical military facility or command post. They are also vulnerable to the blinding effects of nuclear explosions in the atmosphere.

Given all these challenges to ballistic missile defense, it is easy to understand why, when engineers have been under intense political pressure to deploy a system, the United States has repeatedly started costly programs that proved unable to deal with key technical challenges and were eventually abandoned as their inadequacies became apparent. As noted in the Introduction, the United States has spent more than $350 billion in 2020 dollars [BMD Expenditures 2021] since 1957 on research and development and deployment of ballistic missile defense systems, none of which have proven effective.

Challenges posed by the adversary's response. Unlike civilian research and development programs, which typically address fixed challenges, a missile defense program confronts intelligent and adaptable human adversaries who can devise approaches to disable, penetrate, or circumvent the defensive system. This can result in a costly arms race. Which side holds the advantage at any particular moment depends on the relative costs of the defensive system, the offensive system adaptations required to defeat it, and the resources each side is prepared to devote to the competition.

During the Cold War, the United States and the Soviet Union each deployed more than 10,000 megaton-class strategic nuclear warheads [Kristensen 2013]. A number of factors contributed to the deployment of such irrationally large forces, but an important one was the concern that nuclear-armed ballistic missiles might be countered, at least in part, by defensive systems. Because it takes a decade or more to develop and deploy major weapons systems and designers hope they will be able to cope with the evolving situation for at least a decade after they are deployed, it is necessary to project the quantitative and qualitative evolution of weapons systems 20 years or more into the future. These projections are, of course, uncertain, and because "it is better to be overprepared than underprepared," there is a tendency for planners to make worst-case assumptions, which accelerate the defense-offense arms race cycle.

The open-ended nature of the current U.S. missile defense program has stimulated anxiety in both Moscow and Beijing. President Vladimir Putin has announced a variety of new nuclear-weapon delivery systems designed to counter U.S. missile defenses. These include hypersonic boost-glide re-entry vehicles; the

Sarmat, a new, larger ICBM capable of carrying many warheads and a wide variety of devices to aid its warheads in penetrating U.S. missile defense systems; the Poseidon long-range, nuclear-powered uncrewed underwater vehicle; and the Burevestnik nuclear-powered long-range cruise missile.

As for China, the DOD assesses that "The PLA [China's People's Liberation Army] justifies developing a range of technologies China perceives are necessary to counter U.S. and other countries' ballistic missile defense systems, including MaRV [maneuvering reentry vehicles], MIRVs [multiple independent reentry vehicles], decoys, chaff, jamming, thermal shielding, and hypersonic glide vehicles" [DOD 2019]. In summer 2021, China reportedly tested a system that launched a maneuvering glide vehicle onto an orbital trajectory [Rogoway 2021]. And China now appears to be building hundreds of new silos that could hold ICBMs [Warrick 2021].

The challenge of obtaining and acting on independent evaluations. It is important to ensure that the missile defense program does not commit itself to technical approaches that are impractical or easy to defeat. One reason so much money has been spent on U.S. ballistic missile defense efforts with little to show for it is that many of these efforts have been initiated in response to presidential advocacy, highly charged political arguments, or the perceived urgency of near-term threats [Mosher 2000]. "In this climate, ideas and programs are not fully conceived or vetted by the Pentagon bureaucracy and the budget process before they are pushed into the spotlight, contributing to poor program design, inaccurate initial cost estimates, and subsequent increases" [Mosher 2000]. As a result, missile defense programs have often neglected the difficulties and risks involved and bypassed normal safeguards, such as the requirements to "fly before you buy" and to achieve positive evaluations by DOD's Director for Operational Test and Evaluation of their effectiveness under battlefield conditions.

One way to ensure that the missile defense program does not commit itself to ineffective or impractical approaches is to obtain independent reviews of all missile defense approaches and then act on them. For more than two decades, the U.S. missile defense program has solicited or been given reviews and reports that have pointed to serious problems with the program. For example, in 1998, a panel commissioned by the Ballistic Missile Defense Organization and led by General Larry Welch found that the program was in a "rush to failure" because it lacked coherence and a realistic plan. The panel recommended that the program be fundamentally restructured [Cerniello 1998; Boese 1999].

In 2010, Congress instructed the Secretary of Defense to arrange for the JASON Defense Advisory Panel to study the discrimination capabilities and limitations of the U.S. ballistic missile defense system [NDAA 2010, Sec. 237]. Seven years later the Missile Defense Agency (MDA) released an unclassified summary of the JASON report [JASON 2010]. Among its recommendations were that "MDA should consider adjusting its priorities to establish alliances with U.S. government-sponsored laboratories and academic groups. These bodies [could be given] full inside knowledge of relevant MDA programs and funding to carry out challenging reviews and simulations as well as to propose alternative concepts. When justified and with the cooperation and support of MDA, these bodies should be involved in testing programs. Their role would be to give independent and authoritative critical reviews of MDA programs; to formulate and simulate alternative concepts and strategies;

and to supply Red Team challenges to the missile defense system."

In 2011, the Defense Science Board warned that "successful operations [sic] of [the system's] components is predicated on an ability to discriminate (in the exo atmosphere) the missile warhead(s) from other pieces of the offensive missile complex, such as rocket bodies, miscellaneous hardware, and intentional countermeasures. The importance of achieving reliable midcourse discrimination cannot be overemphasized" [DSB 2011].

In 2012, Congress mandated a comprehensive, independent review of the U.S. missile defense program by the National Academies [NRC 2012]. The 2012 National Academies report found that the GMD system "lacks fundamental features long known to maximize the effectiveness of a midcourse hit-to-kill defense capability against even limited threats." The report stated: "The hard fact is that no practical missile defense system can avoid the need for midcourse discrimination—that is, the requirement to identify the actual threat objects (warheads) amid the cloud of material accompanying them in the vacuum of space. This discrimination is not the only challenge for midcourse defense, but it is the most formidable one, and the midcourse discrimination problem must be addressed far more seriously if reasonable confidence is to be achieved" (p. 10). It went on to say, "The midcourse discrimination problem must be addressed far more seriously if reasonable confidence is to be achieved" (p. 11). In conclusion, the National Academies report found that "the current GMD system has been developed in an environment of limited objectives (e.g., dealing with an early-generation North Korean threat of very limited numbers and capability) and under conditions where a high value was placed on getting some defense fielded as quickly as possible, even if its capability was limited and the system less than fully tested" (p. 13).

As we explain in the following chapters, some of the challenging problems with the missile defense program that were identified in the reports quoted above and in other reports have been addressed, but they have not been solved.

4. MIDCOURSE INTERCEPT SYSTEMS

The United States has for many decades been pursuing defensive systems to intercept warheads in midcourse. Currently, the sole system deployed to defend the U.S. homeland against an ICBM attack is the Ground-based Midcourse Defense (GMD) system. To increase the overall effectiveness of the system, in 2020 the Missile Defense Agency proposed a "layered" approach in which attempts to intercept ICBM warheads during the midcourse phase using the GMD system would be followed by further attempts to intercept them using two systems not originally designed for defending against ICBMs: the Navy's Aegis BMD system during the midcourse phase and, perhaps finally, a system based on the Army's THAAD system during the terminal phase (see Figure 2).

The development of a U.S. homeland missile defense has been contentious politically and difficult technically. Independent assessments are routinely commissioned to report on these efforts and provide public information on the challenges and prospects of the U.S. midcourse intercept systems. Since 2002, Congress has mandated that the Government Accountability Office (GAO) produce annual reports on the Missile Defense Agency's progress toward its acquisition goals, and the Defense Department's Director of Operational Test and Evaluation issues annual reports on the status of the missile defense test programs. Congress has also commissioned studies such as the 2012 study by the National Academies [NRC 2012], which assessed the GMD system. As discussed below, these reports paint a picture of a program beset by poor management and poor congressional oversight that struggles to make progress. The 2012 National Academies study concluded that "the GMD interceptors, architecture, and doctrine have shortcomings that limit their effectiveness against even modestly improved threats and threats from countries other than North Korea" and deemed the system "deficient with respect to all its fundamental precepts of a cost-effective defense" [NRC 2012].

We now provide an overview of midcourse intercept systems, including potential countermeasures and their possible remedies, and the three elements of the layered approach that is currently being proposed.

Appeal and challenges of midcourse intercept

Overview. The midcourse phase of flight, which begins when the ICBM's final boost stage has burned out and it and the missile's warhead(s) have separated and are moving ballistically above Earth's atmosphere (see Figure 2), presents both advantages and special challenges for the defense. While in the past some midcourse intercept systems were designed to use nuclear weapons to destroy incoming nuclear warheads, today's systems seek to disable or destroy warheads by firing an interceptor with a kill vehicle that will home in on and collide with them at a velocity high enough to cause them to fail.

For a warhead launched from North Korea to the continental United States, the midcourse phase lasts 30 to 40 minutes, long enough that more than one intercept attempt may be possible. But the warhead is only about a meter in length and can appear to radar and infrared sensors as similar to the final stage and other objects that have been discarded or deployed by the missile. Since these objects are traveling in a near-vacuum, relatively simple, lightweight decoys would follow the same trajectory as the warhead and could therefore confuse or overwhelm the defense.

Passive countermeasures. To be successful, a midcourse intercept system must adequately address the discrimination problem—identifying the nuclear warheads in the presence of other objects, such as the rocket's final stage, possibly deliberately broken into pieces, and other intentional penetration aids, such as radar-interfering chaff or decoys, about which the defense is unlikely to have detailed prior information.

Decoys, such as aluminized mylar balloons, can be built to effectively mimic the radar, infrared, and visible signatures the warhead presents to the defense's sensors [Sessler 2000]. Many such lightweight decoys could be deployed with the warhead. The defense would need to engage all objects that could be warheads, potentially depleting its inventory of interceptors.

Instead of building lookalike decoys, the adversary could disperse objects with a range of radar cross sections, apparent temperatures, and flight characteristics by altering their shapes, coatings, and moments of inertia (which affect their in-flight movement). The adversary could also alter the observable characteristics of the warhead or enclose it in a balloon large enough to make it difficult for the interceptor's kill vehicle to strike the enclosed warhead directly enough to disable it.

While the details of which countermeasure strategies North Korea and other states have developed are not in the public domain, the physics and engineering of the techniques involved are well established, and effective countermeasures are likely to be widely available. In 1999, the U.S. national intelligence community assessed that Russia and China's programs to develop countermeasures against ballistic missile defenses were decades old, suggested that these countries were probably willing to sell the technologies, and concluded that emerging missile states would likely have developed their own countermeasures—based, for example, on radar-absorbing materials, booster fragmentation and chaff, jammers, and simple balloon decoys—by the time they flight-tested ICBMs [NIC 1999]. North Korea has demonstrated a number of relevant technologies, including the capability to deliberately break up a rocket stage, which if applied to the final stage of an ICBM could create debris with radar cross-sections similar to that of the re-entry vehicle [Talmadge 2016].

In its tests of shorter-range missiles, North Korea has demonstrated the ability to launch multiple missiles simultaneously and to deploy a maneuvering re-entry vehicle, indicating investment in strategies to defeat missile defenses by saturating or evading them [UN 2017, Item 12; Gallo 2021]. Some techniques, such as the use of lookalike decoys, might need to be flight-tested to provide assurance that they work, while others, such as anti-simulation balloons (balloons that enclose warheads to camouflage them), might be tested adequately unobserved in ground facilities.

Attacking the defense as a countermeasure. Rather than confusing the defensive system's sensors, an adversary could instead attack or interfere with them. Long-range midcourse intercept of warheads depends on a geographically spread chain of sensors, primarily radars, for tracking and discrimination. Continuous observation of the threat cloud is important both to prevent tracking errors from growing and to attempt to identify the warhead within the threat cloud. An adversary could try to disable key sensors, especially forward-based radars that are within the reach of short- and intermediate-range missiles.

The adversary could also confound sensors without attacking them directly by creating radar and infrared blackout effects with high-altitude nuclear detonations [Garwin 1968]. Incoming warheads could be designed to detonate before an interceptor reaches them, using the long-established technology of proximity fuzes, or the warheads could detonate, either intentionally or accidentally, when struck by an interceptor. A nuclear detonation at an altitude of 100 to 1,000 kilometers would create a large volume of ionized gas that would attenuate radar signals passing through it. For example, a 1 megaton detonation at 400 km would create a cylindrical ionized region more than 400 km in diameter, extending within 15 minutes from below 300 km to nearly 1,000 km altitude. Radars would have difficulty tracking any targets behind this ionized region [Dolan 1972, Fig. 8-6]. Variations of the ionization density would refract radar signals and create directional errors.

Department of Defense research in 1963 investigated the effects of a high-altitude ionized region on radar tracking of warheads and found that even ionized regions one to two orders of magnitude less dense and much smaller than expected from a nuclear detonation produced ultra-high frequency (UHF, 0.3–3 GHz) radar tracking errors averaging 4 km and variations in the apparent radar cross-section of a factor of 10,000 [DNA 1963]. UHF tracking radars, such as those the GMD system relies on, would therefore be unable to accurately track objects in or behind such an ionized cloud. As attenuation scales with the inverse square of the frequency, the higher-frequency S- and X-band (2–4 and 8–12 GHz) radars fielded for the current GMD system would experience much less attenuation and be better able to track objects in the threat cloud [Canavan 2003, Fig. D.1]. However, fluctuations in the radar signatures of the warhead and other objects would make discrimination significantly more difficult.

Less well studied are the high and spatially variable infrared backgrounds that nuclear detonations would produce over similarly large areas. The infrared homing sensors of the midcourse systems' kill vehicles may find it impossible to detect incoming warheads and associated objects against such a background [Stair 1993].

In summary, nuclear weapons detonated at high altitudes are countermeasures within reach of North Korea that could make midcourse tracking and discrimination extremely challenging and could potentially defeat any current or planned midcourse defense.

Multiple intercept attempts. Theoretically, the defense's effectiveness could be increased by making multiple intercept attempts, if failure modes are independent. But using multiple interceptors will not improve the system's performance if the failures are due to a common design flaw or an inability to discriminate the warhead.

Also, this strategy would rapidly deplete the interceptor inventory—especially if warheads cannot be discriminated from decoys. The defense could conserve interceptors with a "shoot-look-shoot" strategy, in which intercept attempts are sequential and cease upon confirmation that the target has been destroyed. However, the current GMD system has a relatively small number of interceptors and has never been tested in shoot-look-shoot mode. Nor does it appear to have a sensor system that could effectively distinguish a warhead from credible decoys or reliably confirm the warhead's destruction. A new GMD interceptor design with multiple kill vehicles could increase the number of targets that could be intercepted, as could inclusion of Aegis Standard Missile-3 (SM-3) IIA interceptors in the homeland defense system. But a shoot-look-shoot strategy provides little advantage if the warhead cannot be discriminated from numerous decoys.

Proposed midcourse intercept systems that could better distinguish warheads from decoys and execute a shoot-look-shoot strategy, such as the GMD-E system [NRC 2012], would rely on concurrent, long-duration observations by X-band radars and infrared sensors. However, the MDA instead plans to rely on the S-band Long-Range Discrimination Radar under construction in Clear, Alaska, and has fielded an experimental kill assessment system based on commercial satellite-hosted infrared detectors. The latter, Space-based Kill Assessment (SKA) system's 22 sensor payloads are sets of three passively cooled single-pixel photodiodes [Sherman 2019]. They have no tracking capability, but instead detect flashes for analysis. This system was not designed to determine whether the intercepted object was a warhead or a decoy. While it might be able to distinguish the destruction of a massive re-entry vehicle from a light balloon decoy, it is less clear that it could tell if the destroyed object was a re-entry vehicle or part of a rocket booster. A recent GAO report raised several concerns about the system and noted that missile defense commanders did not regard "SKA—and its intended design—as a proven, operationally sustainable solution" [GAO 2017, 59]. The success of such an approach requires North Korea to make only limited progress fielding countermeasures.

Other initiatives to increase the U.S. midcourse intercept systems' ability to discriminate warheads from other objects include a program to use lasers hosted on drones to illuminate and image the threat cloud, though discriminating objects on the basis of their appearance in visible light is unlikely to be effective against anti-simulation countermeasures and such a system would be operationally complex to field. This program's funding was zeroed out in the FY22 budget request [DOD 2021].

While including multiple kill vehicles on an interceptor in place of a single, larger kill vehicle does not help discriminate warheads from decoys, this strategy makes more kill vehicles available to intercept more targets, potentially improving the system's effectiveness when its ability to discriminate is poor. The multi-object kill vehicle project was canceled in 2009 and resurrected in 2015, and it again lost its funding in 2019. This feature may be included in the next-generation GMD interceptor that is being developed.

Ground-based Midcourse Defense system

Overview. The Ground-based Midcourse Defense (GMD) system (see Figure 3) is designed to destroy warheads above the atmosphere using the force of impact of a kill vehicle. It comprises 40 interceptors based in underground silos at Fort Greeley, Alaska, and four at Vandenberg Air Force Base, California; a suite of space-based sensors and ground-based radars; and a command, control, and communications system. Considerable resources have been expended on this system. It is expected to cost around $90 billion, one of the most expensive Pentagon systems ever developed. (The GAO's estimate in 2018 was $67 billion in 2017 dollars [GAO 2018, 70], which does not include the expansions proposed in the 2019 Missile Defense Review, estimated to cost $9 billion [CBO 2021], or a new interceptor effort, estimated to cost $18 billion [Judson 2021a].)

The system's technical roots are in the national missile defense (NMD) research efforts of the

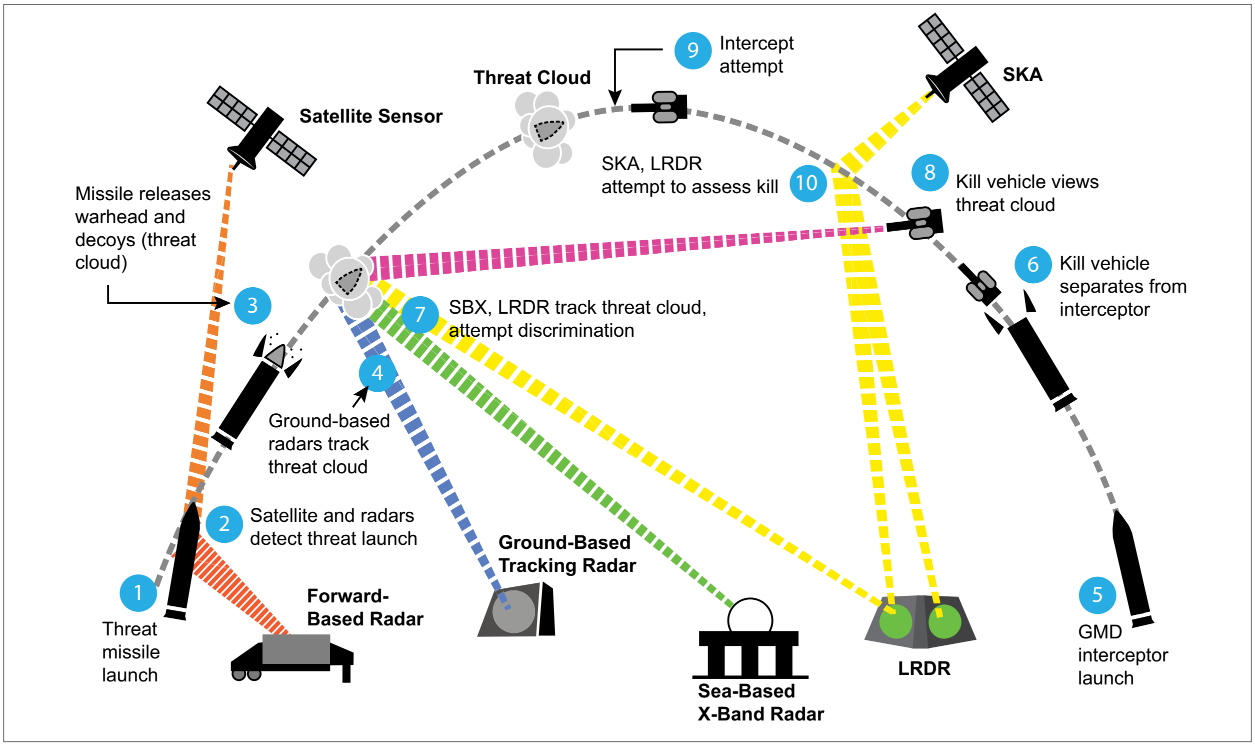


Figure 3 Sequence of events in an attempted intercept by the GMD system. The launch of a threatening ICBM from North Korea (1) is detected within a minute by forward-based radars and satellite-based infrared sensors (2). At the end of the boost phase, the ICBM deploys its warhead and decoys (3). In this example the decoys are balloons, and a balloon encloses the warhead. The warhead, decoys, and any other accompanying objects that must be discriminated from the warhead are referred to as the "threat cloud." Long-range ground-based tracking radars begin to track the threat cloud (4). Based on this information, the GMD system launches one or more interceptors from Alaska and/or California (5), each of which launches a kill vehicle (6) toward the predicted intercept point (9). If a discrimination radar, such as the Sea Based X-band Radar or the Long-Range Discrimination Radar (LRDR), is in place, it will observe the threat cloud (7) to try to determine which object is the warhead and will pass this information to the kill vehicle. The kill vehicle also uses its own, onboard infrared sensor to observe the threat cloud (8) and attempt to determine which object is the warhead. The kill vehicle then steers itself into the path of the chosen object and attempts to destroy it by the force of impact (9). The GMD system attempts to confirm the destruction of the chosen object using ground-based radar (LRDR) and Space-based Kill Assessment (SKA) infrared observations (10). Adapted from [Grego 2016].

1990s. In 2002, the George W. Bush administration withdrew the United States from the U.S.-Soviet/Russian ABM Treaty that limited the two countries' missile defenses, announcing that the United States must urgently field a system to be able to defend against missiles that North Korea, Iran, and Iraq might field [Bush 2002]. It accelerated the deployment of the GMD system to meet a presidentially mandated 2004 deadline. To do so, a streamlined development process exempted from the usual Pentagon "fly before you buy" system was created, allowing the GMD to be fielded with minimal oversight and accountability. The MDA used existing technology and designs, much of which existed only as prototypes, and cut short engineering processes [Grego 2016].

Defense Department officials acknowledged that a development schedule that was driven by externally imposed timelines rather than technical readiness, and the lack of rigorous oversight were sources of significant design and reliability problems [Butler 2014]. Most interceptors were fielded before interceptors with their design had completed even one successful intercept test, and since they were fielded, testing has proceeded at a slow pace, with repeated failures. Two decades later, the testing program remains plagued by delays and reduced test objectives [GAO 2020].

Concept of operations. The GMD system's sensors and interceptors are positioned along the northerly trajectories of land-based ICBMs from potential adversaries—North Korea in particular. Notice of a missile launch would come within a minute from space-based infrared early-warning sensors and forward-based radars, and these data would be used to cue tracking and discrimination radars.

Based on the sensor data, the fire control centers would attempt to discriminate the warhead from other objects, including decoys, and launch one or more interceptors toward potential intercept points. Each interceptor's booster would deploy a 1.4-meter-long kill vehicle. The kill vehicle's onboard computer would choose a target using data from the kill vehicle's cooled charge-coupled device (CCD) sensors, which observe long-wavelength infrared (LWIR) emissions from the threat cloud and compare them with pre-programmed information about the warhead's expected appearance, adding any information it receives via its limited communications from the ground. The kill vehicle would maneuver using divert thrusters to collide at a high relative velocity with its chosen target. (See [Grego 2016] and references therein.) To improve effectiveness, four or five interceptors would be launched at each undiscriminated object, which could be the warhead, a decoy, or debris. Currently, effective target discrimination and a shoot-look-shoot capability are untested aspirations.

Elements of the system. The GMD system's interceptors, which cost about $70 million each, use powerful multi-stage boosters to accelerate the kill vehicle to a speed of about 7.2 km/sec, permitting it to travel long distances (see [Grego 2016], Appendix 6 and references therein). These boosters carry one of three types of kill vehicles, each with a different test success rate (see [GMD Tests 2021]). These kill vehicles are complex and time consuming to build and to repair, leaving them prone to quality control failures [DOD 2014]. The MDA has made seven major attempts to fix the ground-based interceptor (GBI) kill vehicle in the past 15 years. The most recent attempt, the Redesigned Kill Vehicle (RKV), was canceled in August 2019 due to significant technical issues and a tripling of the cost [GAO 2019a].

The current initiative, the Next Generation Interceptor (NGI), has two competing bidders who were selected to develop and build prototype interceptors, with final selection scheduled for 2026. Boeing, the prime contractor responsible for the GMD system, competed but was not selected. The Pentagon estimates an $18 billion lifetime cost for the NGI, including 21 interceptors for deployment and 10 for testing, so each will cost more than half a billion dollars [Judson 2021a]. These interceptors will supplement, not replace, the 44 existing GBIs, starting in 2027 at the earliest. Importantly, few spares of the currently deployed interceptors are available for tests, and no further intercept tests that could be used to better understand the existing system's capabilities are currently scheduled.

The sensors supporting the GBIs include infrared early-warning satellite sensors and forward-based radars, two TPY-2 X-band radars in Japan, and any Aegis ship-based radars in the vicinity when the GMD system is used. U.S.

Aegis ships deploy SPY-1 S-band radars, some of which will be upgraded to SPY-6 S-band radars. These radars cue large UHF tracking radars in Alaska, California, Massachusetts, the United Kingdom, and Greenland. In addition, there are two radars for discriminating targets: the Sea-based X-band radar (SBX), based on a floating platform that is home-ported in Hawai'i, and the S-band Long-Range Discrimination Radar (LRDR) in Clear, Alaska, planned to begin operations in 2021. Japan planned to field two Aegis Ashore sites with SPY-7 radars built with the same technology as the LRDR, but recently canceled these land sites in favor of sea-based platforms [Abott 2021]. If properly placed and incorporated into the U.S. BMD system, those radars could provide S-band coverage of North Korean missiles early in their flight.

The GMD system's current and planned sensor architecture is not well suited for successfully discriminating complex countermeasures from warheads. The warhead and any associated objects become visible as point-like objects in the field of view of the kill vehicle's infrared sensors only about one minute before the kill vehicle's projected impact with the target and cannot be resolved until a few seconds before impact [Grego 2016, Appendix 10]. Once deployed from the interceptor's boosters, current kill vehicles have limited ability to receive and analyze radar and infrared data from other sensors in the system. This limitation is likely to be mitigated in the new interceptor design.

The SBX can provide X-band observations over long parts of expected ICBM warhead trajectories from North Korea, but only if it has been moved in advance to the required location. Even so, the SBX's limited "soda straw" field of view makes it unsuitable for observing multiple ICBM launches in flight at the same time [Willman 2015]. The LRDR should be able to provide long-duration radar observations of multiple missiles, but at a longer radar wavelength and hence with less angular and range resolution. The system is therefore optimized for less sophisticated threats than those assumed in independent studies [Sessler 2000; NRC 2012], which analyzed the performance of countermeasures against larger numbers of X-band radars.

Proposed sensor improvements include a constellation of low-Earth orbiting satellites hosting infrared sensors to track missiles and possibly discriminate warheads from decoys [Cohen 2019; Insinna 2019]. However, the last major effort to build such a system, the Precision Tracking Space System, was terminated in 2013 because it was "too far away from the threat to provide useful discrimination data, does not avoid the need for overhead persistent infrared cueing, and is very expensive" [NRC 2012].

FY20 plans included two large S-band radars similar to the LRDR, one to be sited in Hawai'i and one somewhere else in the Pacific. However, MDA has decided to reassess the sensor architecture and has put the additional sensors on hold [Judson 2020].

Testing program. To incorporate the system into war plans or to decide how to use it under conditions that could include a nuclear attack, decision makers must have reliable evidence of the system's actual effectiveness, but the 20 years of past GMD tests have been conducted under scripted conditions and designed for success. Even so, the system has failed as often as it has succeeded: Of the 19 tests conducted since 1999, the interceptors successfully destroyed their targets 10 times [GMD Tests 2021].

The Pentagon has consistently rated the GMD tests as low in operational realism; realism would require testing against threat-representative targets that include complex countermeasures and with unannounced target launch times [DOT&E 2015]. Only the last two tests have used the warheads of ICBM-range missiles as targets, and in all the successful intercept tests, the time of the test was chosen so that the kill vehicle would see the target brightly lit by the sun against a dark background. And the GMD system has yet to be tested against a salvo of attacking missiles. This is a critical test, because a determined adversary could launch several missiles at once.

Midcourse countermeasures in flight tests. Critically, as of 2021 no GMD flight test had included complex countermeasures, defined by the Director, Operational Test and Evaluation (DOT&E) and the MDA as the "use of target dynamics and penetration aids" [DOT&E 2015, 38]. When tests have included decoys, the decoys have been intentionally designed to be much brighter or much dimmer than the target and the interceptor has been programmed in advance to use this difference to discriminate the target from the decoys [Wright 2019]. It is not publicly known whether any test has included a tumbling warhead, the likely outcome if a warhead has not been intentionally spin-stabilized. A tumbling warhead would present a challenging time-varying brightness to the midcourse intercept system's sensors.

The GMD's slow pace of testing—only 19 intercept tests in 20 years—and the limited realism of the tests is a serious weakness. Other systems deemed important to national security are tested much more frequently. The Trident II submarine-launched ballistic missile, for example, was tested dozens of times before deployment in 1990 and continues to be tested about five times per year (see the Trident II table in [McDowell 2021]). The MDA and the Pentagon testing authority state that increasing the GMD test tempo would require more trained staff and expanded test infrastructure [Gilmore 2015].

There are disincentives, however, to more frequent testing or making the tests more challenging. Since the tests are the most visible indicator of the system's capability, a high value is placed on succeeding. The MDA's position on testing is that "[It] also contributes to U.S. non-proliferation goals by sending a very credible message to the international community on our ability to defeat ballistic missiles in flight, thus reducing their value to potential adversaries" [MDA 2020b]. The tests are also expensive, costing $200 million - $300 million each.

Modeling and simulation (M&S) are critical for the GMD program because of the limited number of tests and because range safety limitations prohibit end-to-end tests over the expected paths of adversary ICBMs using the system's operational sensors. M&S routinely uses optimistic models of the performance of the GMD system and simplistic representation of the operational environment for operational assessments [GAO 2018, 34]. Its threat models have been developed in-house and have not been validated by the Defense Intelligence Agency or accredited by the testing authority [GAO 2018, 32].

Close coordination between the MDA and the intelligence agencies to assess threats was a key recommendation of the JASON report on countermeasures [JASON 2010]. Because of the MDA's special acquisition arrangements, it is not required to seek input from the defense intelligence community, and the defense intelligence community is struggling to provide the MDA timely and detailed information, though efforts are underway to improve this situation [GAO 2019b]. The Pentagon's operational testing office's current assessment is that the M&S effort "lags behind operationally realistic threats with respect to countermeasures, debris, raid sizes, and electronic attack," and that it "remains insufficient to support quantitative effectiveness and lethality assessments" [DOT&E 2021].

Overall assessment. Despite significant investment of resources and decades of effort, the GMD system has not been shown to be reliably effective even in carefully scripted tests, and its effectiveness in battlefield situations is likely to be low. If rigorous engineering procedures are followed in developing a new interceptor, some of the previous design and reliability problems should be addressed. However, even if those improvements are made, the issue of effectively discriminating warheads from decoys will remain unsolved. The MDA has made little progress in this area, and to assess the system as designed as likely to be successful, optimistic assumptions must be made about the adversary's ability to field countermeasures. The system sensors also are not robust against direct attack or high-altitude nuclear detonations.

The National Academies report [NRC 2012] therefore recommended a complete overhaul, including redesigning the system with new interceptors and sensors, and with multiple X-band radars to cover the likely paths of missiles from North Korea and Iran to the United States to make the system more robust to sensor outages. It proposed a concept of operations that relied on a shoot-look-shoot strategy, simultaneous observations of the threat cloud using infrared and visible light sensors and X-band radars over long periods, ongoing communications between off-board sensors and the kill vehicle, and fusing this data to improve the system's ability to discriminate.

The DOD apparently judged it infeasible to start over and instead continues to plan incremental improvements, such as refurbishing existing interceptors, building a limited number of new interceptors, and adding a new S-band radar (the LRDR) in Alaska. At present, the GMD system still does not have continuous X-band radar coverage, nor the ability to fuse data on the threat cloud obtained using the infrared sensors on board the kill vehicle with data obtained using off-board radar observations. The GAO continues to warn that the MDA is developing next-generation systems (in particular the LRDR, the SKA, and the now-canceled RKV) by making "tradeoffs that favor fielding capabilities sooner and less expensively" and which DOD officials are concerned "will compromise performance and reliability" and may end up being insufficient against current and anticipated threats [GAO 2017, 59].

For most of the next decade, therefore, the core of the GMD system will be 44 low-reliability interceptors that would need to be launched in salvos against each credible target (though the system has been tested in a salvo mode only once, using a salvo of only two interceptors). Sometime near the end of the current decade, an additional 21 newly designed interceptors are projected to be fielded. For the simplest of threats, such as a single missile or a few with the type of simple countermeasures the system is designed to handle, this full system may provide some capability. As the Director of Operational Test and Evaluation concluded, when the GMD system can use its complete, proposed architecture of sensors and command-and-control systems, it "has demonstrated capability" to defend the United States against a small number of intermediate range ballistic missiles or ICBMs "with simple countermeasures" [DOT&E 2021].

However, because the system is not designed to reliably discriminate a warhead from decoys, it is likely to quickly exhaust its inventory of interceptors when faced with an attack that includes more missiles and better countermeasures, such as the baseline threat considered in this study. Moreover, this system, which relies on a small number of large radars and satellites with limited redundancy, is not resilient to direct attacks on these sensors.

Due to its fragility to countermeasures, and the inability to expand it readily or cost-effectively, the current midcourse intercept system cannot be expected to provide a robust or reliable capability against more than the simplest attacks by a small number of relatively unsophisticated missiles within the 15-year time horizon of this report.

Potential additional midcourse intercept layers: Aegis BMD and THAAD

The Donald Trump administration proposed using the Navy's ship- and shore-based Aegis BMD system and an upgraded version of the THAAD system to augment the defense provided by the GMD system (see Figure 2). While no proposed locations for these systems have been specified, the MDA estimates that a single Aegis site could defend an area one-fourteenth the size of the area the GMD is designed to defend (which is the United States) [Hill 2020a]. Some analysts estimate that an Aegis site could defend an even larger area, based purely on the speed of the Aegis interceptor (see, e.g., [Butt 2011]). A single THAAD system is designed to defend a much smaller area yet, so many THAAD sites would be needed for a layered defense of the entire United States.

The Aegis BMD system is currently hosted on U.S. Navy cruisers and destroyers and at Aegis Ashore ground sites (one in Romania, one in Poland, and a test site in Hawai'i). Each system includes a four-faced S-band phased-array SPY-1 radar, dozens of vertical launch tubes that can launch SM-3 exoatmospheric hit-to-kill interceptors, and a command-and-control system that can provide target information based on tracking from radars in other locations [CRS 2021b].

The Aegis BMD system was originally designed to defend aircraft carrier battle groups from short- to intermediate-range ballistic missiles. It is becoming increasingly capable as it is upgraded with faster and more sophisticated interceptors; soon, it will also be equipped with more capable shipboard radars. The newest SM-3 Block IIA interceptor may be fast enough to potentially defend large areas of U.S. territory against ICBMs if launched from a site near a U.S. coast. However, it is not clear how well suited the system is for this task, given that intercepting ICBM warheads was not its intended purpose and neither its sensors nor its interceptors were designed for this task. Congress therefore mandated a test of the Aegis system against an ICBM-range missile.

The test was conducted in November 2020. An Aegis ship stationed northeast of Hawai'i destroyed the warhead launched by an ICBM-range missile using an SM-3 IIA interceptor [DOD 2020b]. Despite being executed under highly favorable conditions [GAO 2021], the test stressed the system. At a press event, the Director of the Missile Defense Agency, Vice Admiral Jon Hill, stated that, to intercept the target, the ship had to maneuver to a better location and the interceptor had to use "the highest divert" of any test [Eckstein 2021b]. The GAO states that "several challenges" remain to be overcome to make the Aegis system a workable defense against realistic ICBM threats, and notes that some elements of the SM-3 IIA interceptor may prove to be unsuited to the longer-range ICBM mission [GAO 2021]. One critical issue among many is whether Aegis interceptors can reliably be launched and guided to an ICBM warhead by offboard radars, which would be necessary for the system to potentially cover enough territory to make a meaningful contribution to defending the U.S. homeland against ICBMs. The Aegis system is of course susceptible to the same midcourse countermeasures as the GMD system. Additionally, some Navy officials have expressed frustration that when performing missile defense duties to protect land areas, the very sophisticated and capable Aegis ships are pinned down in geographically small areas and are unable to perform other missions (see [CRS 2021b, 16–19]).

THAAD was designed to defend areas the size of military bases against the warheads of short- to intermediate-range missiles and can attempt hit-to-kill intercepts of warheads at altitudes of 40 - 150 km (within and just above the atmosphere) and ranges of up to 200 km [Reuters 2017]. The suitability of the THAAD system for a local defense against ICBM warheads has not been established or tested. The THAAD system's X-band radar provides better range resolution and discrimination capability than the existing Aegis radars, but before initial tests can be conducted against ICBM warheads (in 2023 at the earliest; see [Sherman 2020]), the system will need crucial upgrades that, among other things, would significantly increase the speed of its interceptor [MDA 2020a]. While THAAD interceptors can intercept within the atmosphere, the system could still be deceived by lightweight midcourse countermeasures until the last minute of the warhead's flight.

Wider implications of planned U.S. midcourse intercept systems

Given the technical realities of the existing U.S. midcourse intercept systems and the limits imposed on their future effectiveness by countermeasures, the enormous planned investments in these systems are likely to provide only incremental rather than comprehensive improvements in their capability. But the unbounded nature of the U.S. missile defense enterprise and the planned dramatic expansion of the Aegis BMD system—even if developed primarily to counter existing threats from North Korea and potential future threats from Iran—has important implications for the strategic relationships between the United States and China and Russia (see also the discussion in Section 3: "Challenges of Missile Defense"; [Baklitskiy 2021], 16 ff; [Erästö 2021]).

The United States plans to have 60 Aegis BMD-capable ships by the end of FY23 [MDR 2019, 48] that will host scores to hundreds of SM-3 IIA interceptors. The GMD and Aegis interceptor inventory will then be much larger than the expected numbers of Chinese missiles that could survive a U.S. first strike. The anticipated deployment of these interceptors is giving China incentives to increase and diversify its offensive nuclear capabilities and disincentives to engage in nuclear arms reductions. China currently has only 72 mobile ICBMs [Kristensen 2020], but it may now be building several hundred new ICBM silos that could be intended to make a U.S. disarming first strike more difficult [Kristensen 2021]. As James Miller, a former Undersecretary of Defense for Policy during the Barack Obama administration, has noted, the objective "to bring the SM-3 IIA missile into the national defense architecture . . . means that China and Russia must expect the United States by 2025–2030 to have many hundreds of available interceptors for national missile defense." He warned, "We should expect the Chinese nuclear arsenal to grow substantially and Russia to resist reductions below the 2010 New Strategic Arms Reduction Treaty—and to prepare seriously to break out" [Reif 2019].

A clear-headed assessment of the economic and security costs of pursuing midcourse defense, together with a careful assessment of its possible benefits, is critical for U.S. security. Given the information presented in this section, it has become increasingly apparent that the drawbacks of the current U.S. midcourse defense program outweigh its potential benefits.

5. BOOST-PHASE INTERCEPT SYSTEMS

Systems that would disable attacking ICBMs during their boost phase—while their rocket engines are still burning and before they have deployed their nuclear warheads—first attracted significant interest in the early 1980s, but no effective system was developed then. Such systems again attracted interest in the early 2000s, as the difficulty of midcourse intercept became increasingly obvious [APS 2003, S2], but careful analyses showed that such systems were still not feasible [APS 2003; NRC 2012].

For example, the 2012 National Academies report concluded, "With one or two minor exceptions, land-, sea-, or air-based boost-phase defense is not feasible when time-line, range, geographical/geo-political, or cost constraints are taken into account" [NRC 2012, S-6]. It also found that the total life-cycle cost of placing and sustaining the number of space-based interceptors required for a boost-phase defense system was at least an order of magnitude greater than that of any other alternative, making the project impractical for that reason alone [NRC 2012, S-7]. Consequently, its first major recommendation was, "The Department of Defense should not invest any more money or resources in systems for boost-phase missile defense. Boost-phase missile defense is not practical or cost effective under real-world conditions for the foreseeable future" [NRC 2012, 4-13].

However, boost-phase systems that would disable attacking ICBMs using rocket interceptors or laser weapons carried by fighter aircraft or drones, or similar systems based on platforms in low-Earth orbit are again being proposed [Abott 2018; NDAA 2018, Secs. 1685 and 1688; Cohen 2019; NDAA 2019, Secs. 1676 and 1680; MDR 2019; MDA 2019, Sec. PE 0604115C; NDAA 2020, Sec. 1682; NDAA 2022, Sec. 1664]. To be reliable and effective, a boost-phase intercept system must have operational capabilities that are not just marginal when used for the intended mission, but sufficient to deal with unexpected events and contingencies. In this chapter we reexamine these types of systems and assess whether anything has changed in the past decade that would alter the conclusions of the National Academies study regarding boost-phase defenses against North Korean ICBMs.

As we explain, the situation regarding boost-phase rocket interceptors based on land has not changed. Unless they could be cooperatively based in China or Russia, they would not be feasible [NRC 2012, S-12, footnote 13]. Nor has the situation regarding sea- or air-based rocket interceptors for boost-phase intercept fundamentally changed; neither approach could protect the entire continental United States; at most they would cover only some limited regions.

As we describe, the number of interceptors required for a space-based interceptor system to be able to defend in principle against North Korea's Hwasong-15 liquid-propellant ICBM is at least 400, and about 4,000 would be required to defend against a salvo launch of 10 such ICBMs. Many times more interceptors would be required to defend against solid-propellant ICBMs, should North Korea acquire them. (We note that Iran is assessed to have the technical and industrial capacity needed to develop ICBMs and in April 2020 launched a satellite using its three-stage solid-propellant Qased rocket, which could probably be transformed into a long-range ballistic missile [Elleman 2021a].) This situation remains very unfavorable for a space-based defense. In principle, the financial costs of building and launching commercial space-based systems have decreased dramatically, but as we discuss, whether these economies could be captured by a space-based interceptor system is unclear. The weaponization of space and arms race instability that would be caused by testing and deploying a constellation of space-based interceptors are significant issues in addition to its technical challenges and cost.

We also note that ICBMs launched from North Korea would need to be intercepted over Chinese territory, hundreds of kilometers inside China's borders. Hence, to respond effectively to a suspected ICBM attack by North Korea, a boost-phase intercept system would have to launch at least several, and perhaps dozens of interceptor missiles over Chinese territory, and their final stages would come down in China or Russia. The consequences of firing such a system by mistake could be very serious. Such a boost-phase system would therefore have to be able to reliably identify the launch of a threatening missile and distinguish it from other events with very high confidence.

Appeal and challenges of boost-phase intercept

Boost-phase intercept systems have attracted attention for several reasons: Intercepting an ICBM during its boost phase could prevent any of its warheads from striking their targets, so a single, effective boost-phase intercept system could in principle defend a very large area; and intercepting ICBMs during their boost phase has sometimes been portrayed as easier than intercepting warheads during the midcourse or terminal phases of flight.

Key challenges of boost-phase intercept. A boost-phase intercept system must successfully and simultaneously deal with a number of challenging problems for which solutions have not yet been demonstrated. Its interceptors must be based on platforms in locations that are geographically and geopolitically feasible and secure, which generally limits their performance, yet be able to reach the target ICBM within about two to four minutes after it has been launched. Consequently, the launch of any threatening ICBM must be detected, its trajectory estimated, a firing solution for the interceptors computed, and interceptors fired less than a minute after the launch of the ICBM has been confirmed by remote sensors. The performance required to intercept North Korean ICBMs during their boost phase would be much less if interceptors could be based in China or Russia (see Figure 4).

An interceptor rocket that strikes an ICBM while it is in powered flight will damage it sufficiently to terminate its thrust, though perhaps not immediately. The collision may be violent enough to cause the warhead to explode, either because it has not been constructed to remain safe if struck, or because it has been designed to explode if it is struck ("salvage fuzing"). If the warhead explodes when the ICBM is hit, the explosion could blind the defensive system's sensors, interfering with its ability to intercept other ICBMs launched at nearly the same time (a "salvo launch"). If the intercept does not cause the warhead to explode, the warhead may remain attached to the ICBM's final stage, in which case both will re-enter the atmosphere together, or the warhead may separate from the ICBM's final stage, in which case it will re-enter the atmosphere separately. Either way, it may detonate when or before it hits the ground [APS 2003, Sec. 13]. We do not consider what would be needed to disable or destroy the warhead, which is a much more demanding task [APS 2003, Sec. 13.2]. This report instead discusses what would be needed to prevent an ICBM's warhead from reaching various parts of the continental United States by terminating the ICBM's thrust sufficiently early.

According to our modeling, preventing a warhead launched by a Hwasong-15 from reaching any part of the continental United States would require intercepting it no later than 260 seconds after it is launched, and preventing a warhead launched by our notional solid-propellant ICBM (which is based on the S1 ICBM in the 2003 APS report) from reaching any part of the continental United States would require intercepting it no later than 145 seconds after it is launched. Intercepting these ICBMs this early would protect cities in Alaska as well as cities on the U.S. East and West Coasts. It would also eliminate the efficacy of a late-stage dog-leg maneuver that would sacrifice range (e.g., hit Alaska instead of Boston) in order to evade the boost-phase defense (see [APS 2003, Sec. 15.2]). ("Dog-legs" are maneuvers in which the missile starts out in one direction and then veers off in another, making it difficult for the defense to anticipate the eventual missile trajectory.)

As noted above, if the intercept is otherwise successful but does not disable the warhead, the warhead will fall short of its intended target but may detonate when or before it hits the ground. For ICBMs launched from North Korea, the resulting nuclear detonation would not occur over North Korea, but over China, Russia, Canada, or locations within the United States that are closer than the intended target. This poses a complex political and humanitarian problem, called "the shortfall problem" (see [APS 2003]). Timing an intercept to prevent a live warhead from falling on other countries and exploding presents a formidable technical problem and may not be possible. The seriousness of this problem is mitigated by the context: such a shortfall would occur during a nuclear war and the warhead would likely explode on an area with a relatively low population. We do not attempt to address this problem in our report (for a detailed discussion of this problem, see [APS 2003, Sec. 5.8]).

While a boost-phase defense could potentially reduce the number of missiles that the midcourse defense would face, it could also make midcourse defense more difficult. For example, if a boost-phase intercept destroys the booster but not the warhead, the intact warhead may then be accompanied by the booster debris, or the warhead may be set tumbling or spinning in ways that the defense has not anticipated (see [APS 2003, Sec. 13.3]).

The reach-versus-time challenge. Boost-phase intercept systems face a severe reach-versus-time challenge because their interceptors must be based in safe or defendable locations, which are typically 500 km or more from the location where the intercept occurs; their interceptors cannot be fired until the ICBM's direction of flight has been determined; and they must reach the ICBM early enough to prevent it from delivering its warhead to a target in the United States. It is difficult even for fast interceptors to achieve this. Whether it is possible depends on many factors, including details of the offense—where the ICBM is based and how long its powered flight lasts (the "burn time" of its boost phase), which depends strongly on whether it is a liquid- or solid-propellant missile and its intended target—and the detailed performance capabilities of the defense—the speed of the interceptor and whether it is fired almost automatically or some decision time is allowed, and whether the system is expected to defend all or only part of the United States. (We use the term "decision time" in the same way as [APS 2003], to refer to any additional time after the ICBM's trajectory is first estimated that can be used for communication between system elements to evaluate whether a reported launch detection is an ICBM or a spoof; to resolve any uncertainties about the performance of the defensive system; and to better identify the type of missile detected, its likely performance characteristics, and its trajectory [APS 2003, xxiii, S70].)

Figure 4 provides a map of North Korea and the adjacent parts of China and Russia with the initial ground tracks of ICBMs launched from north-central North Korea to five cities in the United States. (The initial azimuths of these ground tracks are about 10° farther north than the initial azimuths of the great circles connecting the launch site to the targets because of the effects of Earth's rotation.)

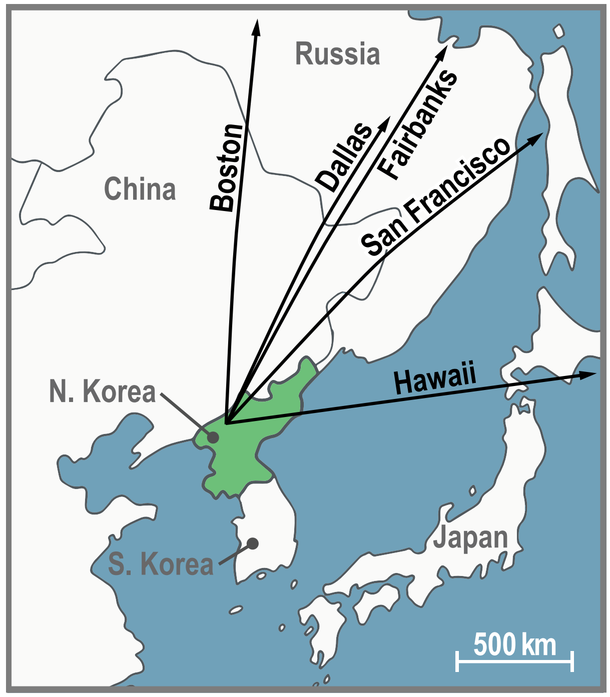


Figure 4 Map showing North Korea and adjacent countries and the initial ground tracks of ICBMs launched from north-central North Korea to five cities in the United States. ICBM ground tracks differ from great circles connecting the launch site to the target because of Earth's rotation.

The kinematically allowed basing area for a given interceptor, decision time, and intercept time is the circular area on the ground centered directly under the point on the ICBM's trajectory where it will be at the moment when it is intercepted. The radius of this area is approximately equal to the distance the interceptor can travel from the time it is fired until the time it intercepts the ICBM (see [APS 2003, Sec. 4.6] for a more precise definition and a more detailed discussion). The kinematically allowed basing area is larger the later the ICBM can be intercepted and is largest if the ICBM can be intercepted just before it gives its warhead sufficient velocity to reach the intended target [APS 2003, Ch. 5]. Note, however, that the intended target is generally not known in advance by the defense. Also, some portions of the basing area determined in this way may be unavailable or unsafe places to base interceptors. The possible basing area is that portion of the kinematically allowed basing area, if any, where interceptors can be safely positioned or defended.

Figure 5 illustrates these challenges using a model of North Korea's Hwasong-15 and our notional model of a solid-propellant ICBM launched from a site that favors the offense, but with other assumptions that favor the defense (see below).

Boost-phase intercept of ICBMs launched from even a small country like North Korea is very challenging. As a result, whether an ICBM can be intercepted before it gives its warhead sufficient velocity to reach the intended target depends on the type of ICBM, its target, and the performance of the interceptor, as well as the decision time needed by the defense. This is illustrated by Figures 5(a) and 5(b).

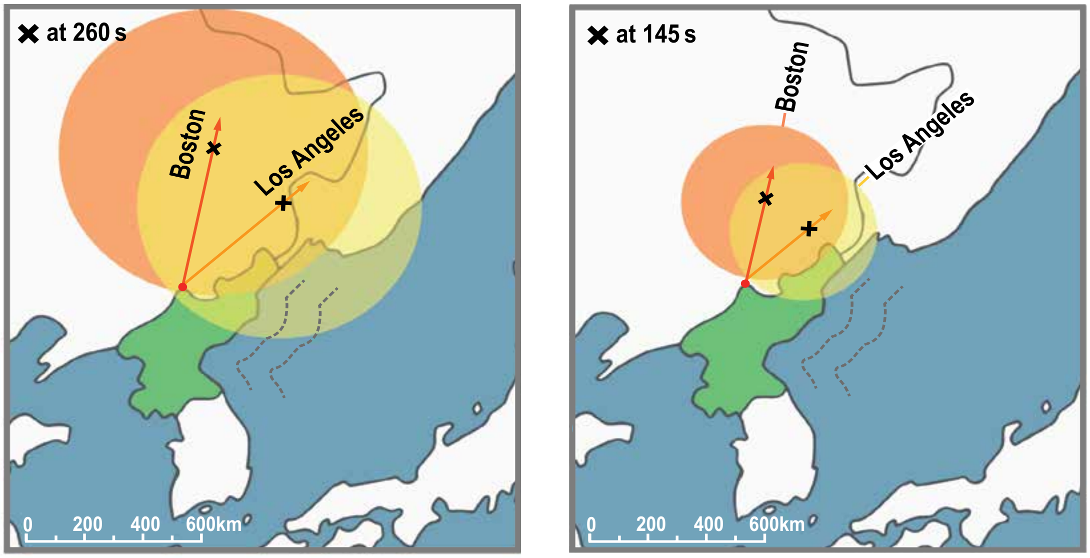


Figure 5: Possible basing areas for the interceptors discussed in the text to be able to reach liquid- and solid-propellant ICBMs launched from North Korea in time to prevent them from delivering their warheads to the indicated target cities. (a) Initial ground tracks of Hwasong-15s launched toward Boston and Los Angeles. Our model of the Hwasong-15 would have to be intercepted no later than 260 seconds after launch to defend all of the continental United States. The positions of the two Hwasong-15s at this time are indicated by the crosses on their trajectories. The colored circular areas show where 5 km/s interceptors could be based and intercept them at this time, assuming the interceptors are fired without allowing any time for a decision whether to fire (zero decision time). The two dashed lines indicate distances of 100 and 200 km from the East Coast of North Korea beyond which interceptors would have to be based to be safe from North Korean defenses, depending on the performance of these defenses (see text). There is no safe basing area that would allow interceptors to reach Hwasong-15s aimed in the direction of Boston. (b) As in (a), but for our notional solid-propellant ICBM. It would have to be intercepted no later than 145 seconds after launch to defend all of the continental United States. The positions of the two solid-propellant ICBMs at this time are indicated by the crosses on their trajectories. The colored circular areas show where 5 km/s interceptors could be based and intercept them at this time, assuming the interceptors are fired with zero decision time. The two dashed lines again indicate distances of 100 and 200 km from the East Coast of North Korea. There are no safe basing areas that would allow these interceptors to reach such ICBMs headed to any place in the continental United States. The limited basing areas shown in this figure reflect the severe reach-versus-time challenge of boost-phase intercept. After [APS 2003, Fig 5.9].

Figure 5(a) shows the kinematically allowed basing areas from which interceptors with the ability to rapidly accelerate to 5 km/s and fired with zero decision time could reach our model of the Hwasong-15s launched from north-central North Korea in the direction of Boston or in the direction of Los Angeles, 260 seconds after they were launched.

The basing areas that would make it possible to intercept Hwasong-15s significantly earlier than 260 seconds after they were launched would be significantly smaller. Importantly, for Hwasong-15s launched from sites in north-central North Korea in the direction of Boston—or in the direction of other cities in the northeastern United States, such as New York—these possible basing areas do not extend outside the territory of North Korea, Russia, and China. Consequently, basing interceptors in them would not currently be politically realistic. The same is true for the basing areas from which Hwasong-15s launched from sites in northwest North Korea could be intercepted. For intercepts significantly later than 260 seconds after launch, the kinematically allowed basing areas would have larger radii, but would be further north and again would not extend outside North Korea, Russia, and China.

As we now explain, even if the intercept could be timed to occur at 260 seconds after the Hwasong-15 was launched, which would require precise knowledge of its performance and intended target, there would be no portion of the kinematically allowed basing area where these interceptors could safely be positioned.

The absence of any safe basing area is shown by the two dashed lines in Figure 5(a), which indicate the distances of 100 and 200 km off the east coast of North Korea beyond which interceptors would be safe while on-station, depending on the assumed capabilities of North Korea's sea and air defenses. The latter may include as many as six batteries of older S-200 surface-to-air missile systems, which have a maximum range of 250 to 400 km, depending on the type, and an unknown number of more modern KN-06 systems that resemble the Russian S-300 or Chinese HQ-9 and are claimed to have a range of 160 km [Yeo 2017]. North Korea has recently tested what it says is a newly developed surface-to-air missile system called the Pon'gae-6 [Kim 2021b; Rahmat 2021]. No portion of the kinematically allowed basing area for intercepting a Hwasong-15 aimed in the direction of Boston extends beyond the dashed lines.

A Hwasong-15 launched from northern North Korea and aimed in the direction of Los Angeles could strike targets in the Aleutian Islands unless it is intercepted earlier than 260 seconds after launch, but could be prevented from striking Los Angeles if it is intercepted earlier than 285 seconds after launch. Figure 5(a) shows that if the defense planned to intercept an ICBM in the direction of Los Angeles as early as 260 seconds after launch, there would be a portion of the kinematically allowed basing area where the interceptors we are discussing could be safely based. If the defense planned to intercept an ICBM aimed in the direction of Los Angeles later than 260 seconds after launch, it could make use of a larger safe basing area or allow some decision time before firing its interceptors. Similarly, there could also be some safe basing locations from which interceptors could intercept Hwasong-15s from northern North Korea early enough to prevent them from striking cities in the Midwest or on the West Coast of the United States, though not cities elsewhere in the United States.

The examples shown in Figure 5(a) illustrate several key considerations of interceptor basing. First, if the interceptors being considered are not based in China or Russia, in most cases they could not reach ICBMs launched toward targets in the continental United States until they are over Chinese territory. Second, to be able to reach Hwasong-15s aimed in the direction of cities on the U.S. East Coast early enough to defend these cities, these interceptors would have to be based too close to the east coast of North Korea to be safe from North Korean air and sea defenses, even if they were fired with zero decision time. Third, there are safe locations where interceptors like these could be safely based and reach Hwasong-15s aimed in the direction of cities in the Midwest or on the U.S. West Coast early enough to prevent them from delivering warheads to those targets, even allowing some decision time. However, it is not to be expected that North Korea would choose to launch ICBMs in directions it knows would make them vulnerable to the defense. A boost-phase defense would be much easier kinematically if interceptors could be based in China or Russia; however, short of extensive cooperation in such a defense, the United States cannot realistically or prudently expect that interceptors intended for defense against North Korean ICBMs can be stationed in Chinese or Russian territory or airspace [NRC 2012, S-12].

Deployment of a boost-phase defense by the United States would give North Korea a strong incentive to develop and deploy solid-propellant ICBMs, because they have much shorter burn times than liquid-propellant ICBMs and the time available to intercept them is therefore much reduced. This is illustrated by Figure 5(b), which shows there is no safe basing area from which a 5 km/s interceptor could reach a solid-propellant ICBM launched from northwest or north-central North Korea early enough to prevent its warhead from striking any part of the United States, even if the interceptor were fired with zero decision time.

The kinematically allowed basing areas shown in Figure 5 make the same assumptions that were made in the 2003 APS study, which generally favor the defense [APS 2003, xxvi]. For example, they make optimistic assumptions about the missile detection and tracking capabilities available to the defense. They also assume that the interceptor is fired at the earliest moment a firing solution can be constructed.

A firing solution cannot be constructed as soon as an ICBM is launched. When it would become available depends on a number of factors, including the type of ICBM, what remote sensors are available, meteorological conditions at the time, and the capabilities of the interceptor (see [APS 2003], Section 2.4.1, for a detailed analysis and explanation). For a liquid-propellant ICBM like the Hwasong-15, this is expected to be possible about 65 seconds after it is launched, about 20 seconds after the launch is first detected by remote sensors. For a typical solid-propellant ICBM, a firing solution is expected to be available about 45 seconds after it was launched, about 15 seconds after the launch has been detected [APS 2003, Fig. 2.2; NRC 2012, Figure 2-3]. The 2012 National Academies study found that it is counterproductive to commit an interceptor earlier than these times [NRC 2012, 2–27]. Committing interceptors this early means they must be fired almost automatically, i.e., with no decision time. Allowing 30 seconds of decision time would reduce the radii of the kinematically allowed basing areas by about 150 km for a 5 km/s interceptor, making intercepting even a Hwasong-15 aimed in the direction of Los Angeles substantially more challenging. That all these times are very short reflects the severe reach-versus-time challenge of boost-phase intercept [NRC 2012, S-11]. The time available might be increased if distributed sensors and machine learning allow as-yet-unquantified improvements in estimating the trajectory of the target ICBM quickly and deciding whether to fire interceptors.

The kinematically allowed basing areas shown in Figure 5 also assume the interceptor has a burnout velocity of 5 km/s, which is slightly higher than the maximum velocity of a rocket interceptor based on current technology that could fit in an Aegis vertical launch system tube [NRC 2012, 2-17] and the highest velocity that has been proposed for airborne rocket interceptors [Garwin 2018a; Garwin 2018b]. The calculated basing areas further assume a very fast-burning interceptor, which burns out after only 25 seconds, about half the burn time of the 5 km/s interceptor used in the 2003 APS study [APS 2003, Table 5.3]. While shortening its burn time increases the reach of the interceptor by about 60 km, it lengthens the already long duration of the interceptor's coasting phase, when the rocket motor of the booster has burned out but the rocket motor of the kill vehicle has not yet begun firing. During this phase, the interceptor cannot adjust its trajectory to compensate for deliberate or unexpected incidental accelerations of the target ICBM. Lengthening the duration of this phase decreases the likelihood that the interceptor will be able to hit its target [APS 2003, Sec. 2.2, 12, and 14, and Appendices B and C]. Finally, these basing areas do not take into account the possibility that the attacking ICBM could be programmed to use any energy it has beyond the minimum needed to reach its target to fly a dog-leg trajectory to the target that keeps it farther from potential safe interceptor basing areas.

On the other hand, the ICBM launch site assumed in Figures 5(a) and 5(b) is one of the most challenging launch sites for a boost-phase defense, in the sense that trajectories to the United States from northwest and north-central North Korea would be hardest for interceptors not based in China or Russia to reach before the ICBM has achieved the velocity needed to deliver its warhead to a target in the United States. Boost-phase intercept would be easier for ICBMs launched from some other sites in North Korea, but it is not expected that North Korea would choose to launch its ICBMs from such sites knowing that they would then be more vulnerable to intercept.

This discussion also does not account for many of the real-world factors that would have to be considered to realistically assess the capability of a proposed boost-phase intercept system [APS 2003, xxvi and Sec. 5.1.3]. These include lack of knowledge of the locations of the adversary's ICBM launch sites, uncertainties about the performance of its missiles and their possible maneuvers during flight, ignorance of a missile's intended target, the unpredictable nature of the variations in any missile's flight, and uncertainties in how quickly an intercept would terminate the ICBM's thrust. We have also not accounted for possible operational delays in processing and transmitting information. All of these factors must be included when assessing possible boost-phase intercept defenses against ICBMs.

Kill vehicle and system requirements. The kill vehicles carried by boost-phase interceptors must reach the ICBM early enough to prevent its warhead from reaching the target and must have the sensors and cumulative divert velocity required to be able to home in on and hit the dim missile body rather than its bright exhaust plume while the missile is moving at a velocity of about 6 km/s and accelerating and maneuvering somewhat unpredictably [NRC 2012, 2-31]. This requires a sensor such as a light-detection-and-ranging (LIDAR) system and a kill vehicle with a cumulative divert velocity of at least 2.5 km/s [APS 2003, Sec. 12.3.2]. The system's sensors and kill vehicles must not be confused, misled, or distracted by countermeasures the attacker could employ (see below). Finally, the system must be able to handle the complex battle management task of assigning multiple interceptors to multiple attacking ICBMs and guiding the kill vehicles to their targets. It must be able to do this even if confronted with debris created by successful previous intercepts.

Countermeasures. Although a boost-phase defense would not be susceptible to some of the countermeasures to midcourse defense that have been proposed, it would face countermeasures [APS 2003, Ch. 9; NRC 2012, 2-31]. In order to avoid arguments about what countermeasures to boost-phase intercept are or are not feasible, the 2003 APS report considered only techniques that have actually been employed in operational systems over the past 60 years and that North Korea is therefore likely to be able to implement. Examples include (a) launching several ICBMs nearly simultaneously (salvo or staggered launch); (b) launching smaller decoy rockets simultaneously with the ICBM, to confuse the defense; (c) deploying solid-propellant ICBMs, with their much shorter burn times; (d) deploying the ICBM's warhead (re-entry vehicle) while its final stage is still burning; (e) deploying rocket-propelled decoys and jammers during the flight of the ICBM's upper stages; (f) programming the upper stages to fly evasive maneuvers, possibly in conjunction with deployment of decoys and jammers; and (g) deploying short-burn boosters with multiple upper stages, each with its own warhead. Each of these countermeasures constitutes an independent and important challenge to boost-phase intercept.

Using land- and sea-based rocket interceptors for boost-phase intercept

As discussed in the previous section, land-based rocket interceptors would have to be based in China or Russia, north of potential launch sites in North Korea, to be able to intercept even a long-burning, liquid-propellant ICBM like the Hwasong-15 launched from northwest or north-central North Korea toward the U.S. East Coast, in time to prevent its warhead from striking the United States.

Sea-based rocket interceptors small enough to fit in Aegis vertical launch system (VLS) tubes would have maximum burnout velocities slightly lower than the 5 km/s burnout velocity assumed in the previous discussion. They therefore also could not reach an ICBM like the Hwasong-15 launched from northwest or north-central North Korea toward the U.S. East Coast in time, even if the Aegis ships were positioned within 200 km of the east coast of North Korea or Russia and the interceptors were fired with no decision time. Depending on its maximum range, an ICBM like the Hwasong-15 could also evade intercept by starting on a trajectory toward the U.S. East Coast and then shifting its trajectory to strike cities in Alaska or the U.S. Northwest. Interceptors launched from ship-based VLS tubes could intercept long-burning liquid-propellant ICBMs aimed in the direction of cities on the U.S. West Coast. In order to be able to attempt intercept of a salvo of 10 such ICBMs, VLS tubes would have to be preloaded with 10 or 20 interceptors, depending on their expected effectiveness against ICBMs and the expected countermeasures. Interceptors launched from VLS tubes would be unable to intercept solid-propellant ICBMs headed to the United States.

Aegis ships are being considered for use as platforms for rocket interceptors that would be used for intercepting ICBM warheads late in their midcourse flight, but this has been criticized as an inefficient use of these expensive, very capable ships [CRS 2021b, 16-19]. The same criticism could be made of continuously basing Aegis ships off the coast of North Korea and Russia, as part of a boost-phase defense. This criticism would be less relevant if the plan were to surge ships to positions off North Korea and Russia in case of high tensions or a crisis [MDR 2019, XV and 56]. Interceptors launched from Aegis ships could not intercept solid-propellant ICBMs headed to any targets in the continental United States.

Using drone-based rocket interceptors for boost-phase intercept

A system of drone-based rocket interceptors for a boost-phase defense against ICBMs launched from North Korea would avoid the discrimination problem faced by all midcourse intercept systems and could be designed not to threaten current Russian or Chinese ICBMs [Garwin 2017; Goodby 2018]. It would require high-altitude, long-duration drones able to carry high-speed rocket interceptors with kill vehicles capable of intercepting a maneuvering ICBM (for further information, see [Garwin 2017; Garwin 2018a; Garwin 2018b; Goodby 2018; Postol 2018]).The drones would need to loiter on-station for tens of hours and, as noted above, might have to stay 100 to 200 km off the coast of North Korea to be safe from North Korean air defenses.

As noted previously, such a system armed with 5 km/s interceptors could not defend against even long-burning, liquid-propellent ICBMs like the Hwasong-15, if the ICBMs were launched from sites in northwest or north-central North Korea toward cities on the U.S. East Coast, even if the interceptors were fired with zero decision time. Depending on their range, ICBMs like the Hwasong-15 could also avoid such a defense and strike cities in Alaska or the U.S. Northwest by starting on a trajectory toward the U.S. East Coast to avoid intercept and then changing their trajectories. Drone-based rocket interceptors like these could defend against ICBMs launched from northwest or north-central North Korea, if the ICBMs were aimed in the direction of targets on the U.S. West Coast or were launched from other sites in North Korea that would make them vulnerable to such a defense.

If North Korea were eventually to deploy solid-propellant ICBMs, which typically have full burn times of 180 seconds or less, they could be launched from many sites in North Korea that would prevent them from being intercepted by 5 km/s interceptors (see Figure 5(b) above and [APS 2003, Fig. 5.9]).

Some proposals for developing and deploying drone-based rocket interceptors quickly and cheaply have advocated using already available, off-the-shelf parts [Garwin 2017; Garwin 2018a; Garwin 2018b]. However, the particular boosters and kill vehicles that have been proposed have burn times so short that they could be steered during only a small fraction of the time the ICBM is in powered flight preceding the intercept attempt, reducing the chance that they would be able to intercept the ICBM reliably (see [APS 2003], Sections 2.2, 12, and 14, and Appendices B and C). If a decision were made to develop a defensive system that would use drone-based rocket interceptors, it would probably be necessary to use more capable interceptors and kill vehicles designed specifically for this mission. It would likely also be desirable to develop and deploy drones with flight times longer than current drones and capable of carrying heavier interceptors.

Interceptors, kill vehicles, and drones optimized for this purpose could be developed and deployed within the time horizon of this study, if a decision were made to do so. Concepts of operation, basing locations, and the number of drones that would be required to defend against a single North Korean ICBM or a salvo launch of 10 have not been studied.

The strategic and arms race implications of developing, testing, and deploying a large system of transportable, high-altitude, long-duration drones armed with high-velocity, highly capable rocket interceptors could be profound, unless agreed confidence-building measures could be developed and adopted to reassure Russia and China that these weapons could only be used to defend against ballistic missiles launched by North Korea.

Using aircraft-based rocket interceptors for boost-phase intercept

A system for boost-phase intercept of North Korean ICBMs that uses fighter aircraft (e.g., F-16s or F-35s) armed with endoatmospheric missiles such as the AIM-260 that can steer only within the atmosphere would require fighters to operate within 100 to 200 kilometers of the ICBM launch site, hence over

North Korean territory, for the missile to reach the ICBM before it reaches altitudes greater than 30 km, where such interceptors cannot operate. Operations with piloted aircraft over unfriendly territory inevitably risk pilot capture and serious geopolitical consequences. Aircraft could be used safely for this purpose only if the United States has suppressed North Korean air defenses.

Using space-based rocket interceptors for boost-phase intercept

The limitations imposed on the performance of boost-phase intercept systems that use surface-based interceptors by geographical and geopolitical constraints on interceptor basing locations could be sidestepped by placing the interceptors in low Earth orbit. For such a system to be potentially effective, at least one interceptor must be in position to intercept every ICBM that is launched before the ICBM can give its warhead the velocity needed to reach the intended target. But any space-based interceptors would continuously orbit Earth, Earth would be rotating beneath its orbit, and an adversary could launch multiple ICBMs at times of its choosing. There must therefore be many interceptors in any such system for it to be effective.

In this section we explore the implications of the differences between the current situation for space-based interceptors and the situation considered by the 2003 APS and 2012 National Academies studies. On the one hand, North Korea's current ICBM, the Hwasong-15, has a full burn time of 290 seconds, significantly longer than the 240-second burn time of the liquid-propellant model ICBM considered by these studies. The longer burn time reduces the reach-versus-time challenge somewhat, making boost-phase intercept easier. Also, advances in technology since those studies were performed have reduced the masses of the interceptors that would be needed as well as their construction and launch costs. On the other hand, both U.S. government and nongovernmental sources assess that North Korea now has, or could field within the 15-year time horizon of this study, 10 or more nuclear-armed ICBMs (see Section 2, North Korea's ICBM Capabilities). Having to defend against 10 or more nuclear-armed ICBMs is much more challenging than defending against a single ICBM, which was the potential threat considered by the 2003 APS and 2012 National Academies studies [APS 2003; NRC 2012].

Required size of a space-based interceptor system. As noted above, to be effective, a system of space-based interceptors must ensure that at least one would be in range at all times to intercept any ICBM launched against the United States. We emphasize that the assumptions used to design such a system would need to be conservative, in the sense that it would need to anticipate the possible types and performance of North Korea's ICBMs a decade or more in the future, because it would take a decade or more to design and construct such a system of space-based rocket interceptors and a similar time to significantly increase its capabilities. One would not want to deploy a system that turns out to be ineffective the day it becomes operational.

Assuming that the system would not attempt to defend any cities in Alaska or in the northern parts of the U.S. East and West Coasts or in the Midwest, making several other optimistic and simplifying assumptions (see below), and using the methodology of the 2003 APS Study [APS 2003, Ch. 6], we estimate that if a system were constructed assuming that interceptors would be fired almost automatically, i.e., with no time allowed for a decision whether to fire once the initial trajectory of the ICBM has been estimated, a constellation of about 1,600 space-based interceptors would need to be deployed to ensure that at least one would be in position to intercept each of a rapid "salvo" of four liquid-propellant ICBMs like the Hwasong-15 launched within three minutes or so (see Figure 6), and 4,000 would need to be deployed to attempt to counter a salvo of 10 such ICBMs. If instead the system were designed to allow 30 seconds to decide whether to fire its interceptors, about 2,200 interceptors would be needed to attempt to counter a rapid salvo of four ICBMs and about 5,500 would be needed to attempt to counter a rapid salvo of 10.

Orbital motion of the interceptors would repopulate the coverage that such a constellation would provide on a timescale of about 200 seconds, so if the defense could be certain that all ICBM launches would be spaced at intervals greater than 200 seconds, it could treat multiple launches as a series of single launches. A system designed to be able to defend against only one Hwasong-15, without allowing any decision time, would need at least 400 interceptors. At least 500 interceptors would be needed if it was constructed to allow 30 seconds of decision time.

If North Korea were to eventually deploy solid-propellent ICBMs, which typically have burn times of only about 170 seconds, and a space-based interceptor system was constructed to allow no decision time before its interceptors are fired, a constellation of about 16,000 interceptors would be required to defend against a salvo of 10 ICBMs. In order to allow 30 seconds of decision time, about 36,000 interceptors would be required.

These estimates assume that all interceptors are in orbits inclined 45° relative to Earth's rotation axis, are distributed roughly uniformly over the portion of Earth's surface that they cover, and would have an average acceleration of 10 g to a final velocity of 4 km/s. We

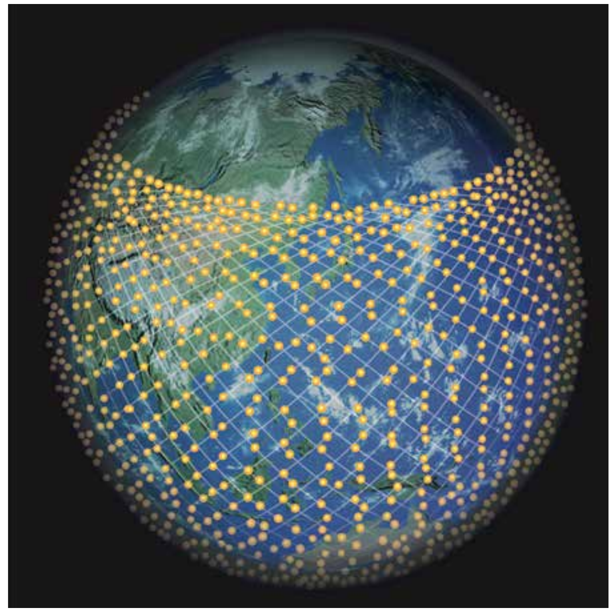


Figure 6 View of Earth showing the constellation of 1,600 space-based interceptors that would be required to ensure that one is available to intercept a rapid salvo launch of four Hwasong-15 ICBMs from North Korea, if the system was designed to fire interceptors almost automatically, i.e., if no time is allowed to decide whether to fire them. If instead the system was designed to allow 30 seconds to decide whether to fire interceptors, about 2,200 interceptors would be needed to ensure that enough are available to intercept such a salvo. See text for details. After [NRC 2012, Fig. 2-20].

have chosen a final "flyout" velocity of 4 km/s because the 2003 APS study found that for its baseline system, a two-stage interceptor with a flyout velocity of 4 km/s minimized the total system mass for a kill vehicle with a 2.5 km/s cumulative divert capability that is capable of a 15 g acceleration in the endgame of the intercept and has an interceptor with a total lag in its response of less than 0.1 seconds [APS 2003, Sec. 6.5].

Just like our estimates for sea-, land-, or aircraft-based interceptors defending against the Hwasong-15, these estimates assume the Hwasong-15 could be detected with confidence 45 seconds after it was launched. They also assume that the ICBM's trajectory would be sufficiently well understood within another 20 seconds that a firing solution could be constructed, enabling space-based interceptors to be fired 65 seconds after the launch of the ICBM if the constellation of interceptors is designed to have no decision time before interceptors are fired. If the interceptors can be fired 65 seconds after the ICBM is launched, they would be able to reach ICBMs about 1,000 km from the position where their launch platform would be 285 seconds after launch. This is the latest time at which the ICBM could be intercepted during its longest burn-time trajectories, the trajectories that are the most favorable for the defense.

As noted above, these estimates assume that the system would not attempt to defend any cities in Alaska or in the northern parts of the U.S. East and West Coasts or in the Midwest. To defend cities in the northern United States, the system would have to be designed to be able to intercept the Hwasong-15 no later than 275 seconds after it was launched, which is 10 seconds earlier than we have assumed in the estimates cited above. To defend cities in Alaska, the system would have to be designed to be able to intercept the Hwasong-15 no later than 260 seconds after it was launched. Constructing a system that could defend these targets would require many more interceptors than the estimates provided above.

When defending against our model solid-propellant ICBM, these estimates assume the system could detect the ICBM 30 seconds after it was launched and a firing solution constructed during the next 15 seconds, so that interceptors could be fired 45 seconds after the ICBM was launched if the constellation were constructed to have no decision time before it fired its interceptors. While we assumed above that intercept is possible as late as 165 seconds after launch, 10 seconds less would be available to defend cities in the northern United States, and 20 seconds less to defend cities in Alaska.

If any additional time is allowed to assess whether a launch has occurred, determine whether it is a spoof, better determine the type of missile, or correct any operational errors, the number of interceptors needed would be correspondingly larger. Additional interceptors would also be required if they are not perfectly reliable or could be defeated by any of the countermeasures against boost-phase intercept described earlier. The methodology of the 2003 APS report guarantees that there is at least one interceptor in range for every ICBM at any given time, although often there is more than one.

While in orbit, each interceptor would need a "lifejacket" or "garage" to provide necessary services (such as electrical power and communications); this would stay behind when the interceptor flies out. It may be advantageous to place two interceptors on each orbiting platform ("satellite") to reduce costs and provide some redundancy [APS 2003, Sec. 6.3]. If the interceptors are placed in orbits that are only slightly more inclined than the latitudes of the required ICBM intercept points, the concentration of satellites at latitudes close to the orbital inclination [Washburn 2013] could in principle allow a reduction in the number of interceptors required, perhaps by as much as a factor of two. However, the substantial spread in the latitudes of the intercept points for ICBMs aimed at different parts of the United States and the inability of the defense to determine the intercept points in advance may limit this reduction in practice.

Cost of a space-based interceptor system. The 2003 APS study (see [APS 2003, Table 14.2]) estimated an interceptor mass of 549 kg for an interceptor with a performance comparable to that assumed above using technology it projected would be available by 2015 [APS 2003, Sec. 6.9]. Further advances in electronics and sensors would almost certainly allow them to be made even less massive today. Garwin and Postol [Garwin 2017; Garwin 2018a; Garwin 2018b] have suggested that this mass could be reduced by 50% using current technology. For this report, we assume a more modest 30% mass reduction and hence an interceptor mass of about 400 kg, plus a garage with a mass equal to 50% of the interceptor mass. Defending against the launch of a single Hwasong-15 liquid-propellant ICBM using a 400-interceptor constellation would then require placing about 240 tonnes in low Earth orbit (LEO), while defending against a salvo of 10 Hwasong-15s would require about 2,400 tonnes in LEO.

Using NRC cost estimates [NRC 2012], the major costs for an initial deployment would be $19 million to $32 million per tonne for on-orbit hardware and $13 million to $22 million per tonne for launch. This implies an initial cost of $8 billion to $13 billion for a system of 400 interceptors designed to defend against a single Hwasong-15, if the system is designed without allowing any time to decide whether to fire interceptors, or $100 billion to $180 billion for a system to defend against a salvo of 10 Hwasong-15s, if the system is designed to allow 30 seconds to decide whether to fire interceptors. There would be additional costs as platforms are replaced over the lifetime of the system. If this estimate holds, even to within a factor of 10, the cost of space-based interceptors is highly unfavorable to the defense. The offense can add one more ICBM to a salvo launch, at about $20 million in 2021 dollars (based on U.S. Minuteman III costs [MMIII Costs 2015]), driving the defense to spend 1,000 times more to match the additional threat. If North Korea were to deploy solid-propellant ICBMs, the number of interceptors required, and the cost of the system, would become four times larger.

Commercial entities have built and launched space hardware at costs dramatically lower than those assumed in the 2012 National Academies report. However, there is no instance of a DOD procurement taking advantage of such economies at the systems level, which would require substantial reductions in the cost of space hardware as well as launch costs.

Commercial launch services have reduced the cost to LEO by a factor of 20, and costs are expected to continue to decline [Jones 2018]. The current cost for launching 23 tonnes into LEO using a fully expendable Falcon 9 rocket is $2,700 per kg, whereas launching 63 tonnes into LEO using a fully expendable Falcon Heavy rocket costs about $1,400 per kg [Jones 2018]. The latter cost per tonne is 9 to 16 times smaller than that assumed in the 2012 National Academies study. The cost per kg using a reusable Falcon Heavy rocket would undoubtedly be significantly less. The Starlink program proposes to launch 12,000 satellites totaling 3,000 tonnes into orbit for a cost of approximately $10 billion, or about $3 million per tonne for both hardware and launch costs [Najjar 2020]. Elon Musk states that each SpaceX Starship rocket will be able to place 100 tonnes in LEO at an operational cost of $20 per kg [Bender 2021]. Reductions in launch costs by such large factors could drive down the costs of space-based interceptors by an order of magnitude or more. However, in commercial space activities such economies of scale often come with built-in reduced reliability, and if so it is not clear that this increased risk would be acceptable for a missile defense system that must work with extremely high reliability.

Countermeasures to space-based interceptor systems. Besides the countermeasures to boost-phase missile defense already described, a space-based system would likely be vulnerable to interference, damage, or destruction by anti-satellite weapons, and might be attacked or sabotaged when interceptors are first orbited, to prevent an effective system from being assembled.

Other disadvantages of space-based interceptor systems. The large constellation of orbiting satellites required for a space-based interceptor system may be threatening in and of itself, since these weapons would essentially blanket the sky (see Figure 6). A system designed to defend against ICBMs launched from North Korea would also threaten China's strategic nuclear forces. If all the interceptors were in orbits with inclinations less than 45°, they would not threaten ICBMs launched from Russia's current launch sites, but such a system could readily be expanded to cover them. With their high burnout speeds and ability to maneuver, space-based interceptors would be potent anti-satellite weapons that could potentially reach all satellites, including those in geosynchronous orbits [Wright 2002]. Fielding space-based interceptors—even just a few in the guise of a testbed—could drive a significant weaponization of space and threaten potential adversaries' sensitive national security satellites. Developing and testing such a system, let alone deploying it, would therefore have major negative strategic and arms race implications.

Using laser weapons for boost-phase intercept

Practical laser weapons for boost-phase intercept would require laser weapons systems compact and light enough to be carried on an aircraft or drone, but powerful enough and well enough focused to be able to disable an ICBM at a realistic standoff distance from the ICBM's trajectory. According to the 2003 APS study, a properly focused 3 MW laser weapon illuminating an ICBM at an altitude greater than 60 km for 5 - 20 seconds could disable a liquid-propellant ICBM at a range up to about 600 km and a solid-propellant ICBM at a range up to about 300 km. These ranges could allow an aircraft carrying the laser to operate 100 km outside North Korean airspace [APS 2003, Sec. 7.3]. This is the performance that was planned for the laser and optics carried by the YAL-1 Airborne Laser aircraft [APS 2003, Sec. 21; NRC 2012, 2-20]. According to Department of Defense officials, current lasers are very far from meeting these performance requirements [Hill 2020b; Mehta 2020].

Efforts to develop and deploy destructive laser weapons are advancing slowly. While MDA has backed away from developing defensive laser weapons, various branches of the U.S. military have continued to pursue this technology [Judson 2021b]. In 2021, the U.S. army demonstrated a 50-kilowatt laser on a combat vehicle intended for short-range air defense, and in 2022 it is expected to acquire a 300-kilowatt technology demonstrator to explore using a laser to defend fixed and semi-fixed sites against cruise missiles, unmanned aircraft and rockets, as well as artillery and mortars. The U.S. navy is currently deploying the HELIOS system on some U.S. destroyers, but it is only destructive at short ranges against relatively soft targets, such as rubber dinghies [Eckstein 2021a; Kubovich 2020]. Israel is developing a 100-kilowatt ground-based laser system that it hopes will be able to destroy targets at a range of eight to 10 kilometers [Ahronheim 2021].

There is widespread agreement that laser weapons that could disable or destroy ICBMs during their boost-phase, whether based on aircraft, drones, or space platforms, will not be technically feasible within the 15-year time horizon of this study (see [Hill 2020b]).

6. CLOSING REMARKS

This report has used publicly available information to consider whether currently deployed and proposed future U.S. missile defense systems could successfully defend the continental United States against an attack by a limited threat: North Korea's current and near-term nuclear-armed ICBM force. Considering these systems in the context of this very limited threat has revealed not only the key technical challenges that would have to be surmounted to address this particular threat, but also the technical challenges that would have to be overcome to address any other possible limited ICBM threats that may arise in the future. Considering the limited threat posed by North Korea's ICBMs now and in the near term has also brought out several broader questions that arise whenever efforts to create a defense against nuclear-armed ICBMs are examined. Nevertheless, there are many technical and non-technical questions about missile defense systems that are outside the primary focus of this study.

On the technical side, we have not discussed how North Korea's nuclear-armed ICBM capability might evolve beyond the 15-year time horizon of this study, or whether other countries might develop a similar ICBM capability in the future. One would need accurate forecasts of the longer-term evolution of these and other possible nuclear-weapon capabilities and the longer-term evolution of missile defense technologies to be able to judge whether defensive systems could meaningfully defend against these potential future threats. We have also not considered what defensive systems, if any, could meaningfully defend against the much more numerous and sophisticated nuclear-armed ICBMs and other nuclear forces of China and Russia.

There are also important non-technical questions that we have only been able to touch on briefly but deserve more extensive consideration and assessment. These include the strategic costs and benefits of deploying a missile defense system that is only partially effective against nuclear-armed ICBMs; the security costs and benefits of pursuing missile defense efforts relative to pursuing diplomatic and arms control efforts; the effects of the U.S. missile defense program on the likelihood that potential adversaries will develop more numerous and advanced offensive nuclear weapons and defensive systems; and the economic and social costs of devoting the very large resources to missile defense that would be required to continue, let alone expand, the current program.

Rather than addressing these and other important but very broad questions, this brief report focused on the fundamental question of whether current or proposed missile defense systems could defend the continental United States against a baseline threat consisting of a single nuclear-armed ICBM launched from North Korea, or a salvo of 10 ICBMs launched in rapid succession (see "North Korea's ICBM Capabilities" section above), once they are launched. We discussed the myriad challenges involved in defending against even one ICBM, challenges that include various possible countermeasures to the defensive system that North Korea could employ (see the "Challenges of Missile Defense" section and the more detailed discussions in the "Midcourse Intercept Systems" and "Boost-Phase Intercept Systems" sections that follow it).

We described the U.S. missile defense systems that have already been deployed, are currently being considered, or have been proposed to defend against nuclear-armed ICBMs. These systems fall into two main categories: midcourse intercept systems and boost-phase intercept systems. The two main sections of the report—"Midcourse Intercept Systems" and "Boost-Phase Intercept Systems"—summarize what is publicly known about the current status, hoped-for capabilities, and future prospects of these two types of systems. Examples of these systems include the GMD midcourse intercept system, the Aegis BMD system when used for midcourse intercept, and the drone-based rocket-interceptor system that has been proposed for boost-phase intercept. We explained the current and near-term abilities of these systems to address the baseline threat and the increased threat that can reasonably be expected within the 15-year time horizon of this report.

What we found is that creating a reliable and effective defense against even the small number of relatively unsophisticated nuclear-armed ICBMs that we considered remains a daunting challenge. The difficulties are numerous, ranging from the unresolved countermeasures problem for midcourse intercept to the severe reach vs. time problem of boost-phase intercept. In addition to many shared challenges, each system has its own unique difficulties that must be overcome. We have detailed these in the "Midcourse Intercept" and "Boost-Phase Intercept" sections of the report.

Our survey of the literature and our analysis of published work has led us to conclude that few of the main challenges involved in developing and deploying a reliable and effective ballistic missile defense have been solved, and that many of the hard problems we have identified are likely to remain unsolved during, and probably beyond, the 15-year time horizon we considered.

STUDY GROUP MEMBERS

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