Strategic Ballistic Missile Defense

CHALLENGES TO DEFENDING THE UNITED STATES

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STUDY GROUP MEMBERS

Frederick K. Lamb (Chair),
University of Illinois

Laura Grego (Co-Chair),
Massachusetts Institute of Technology and Union of Concerned Scientists

James D. Wells (Co-Chair),
University of Michigan, Ann Arbor

William Priedhorsky,
Los Alamos National Laboratory

David Barton,
*Independent Consultant**

Philip E. Coyle,
*Center for Arms Control and Non-Proliferation**

Steve Fetter,
University of Maryland

Alec Gallimore,
Duke University

Cynthia Nitta,
Lawrence Livermore National Laboratory

Aric Tate,
University of Illinois

Institutions are listed for purposes of identification only. Any opinions, findings, conclusions, or recommendations expressed in this report are those of the Study Group members, and do not necessarily represent the official views, opinions, or policies of their institutions.

**Dr. Coyle died after the contents of the initial report had been finalized. Dr. Barton died while the current version was being readied for publication.*

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AUTHORSHIP

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 or their warheads after they have been launched but before their warheads reach their targets. The United States has been pursuing the possibility of a defense against ballistic missiles for more than 65 years. These missile defense efforts have so far cost American taxpayers about $400 billion in 2020 dollars (cf. [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.[1]

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 the accidental or unauthorized launch of one or a few ICBMs by Russia or China [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 striking the United States [CRS 2023; Kristensen 2022], 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 the full Russian and Chinese ICBM forces. Russia and China also have missile defense programs [Baklitskiy 2021], though 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 preemptive 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

[1] The challenges encountered by systems attempting to defend against nuclear-armed intercontinental-range missiles are profoundly different from and much greater than the challenges encountered by systems such as Iron Dome that are designed to defend against conventionally armed, shorter-range missiles. For a discussion of some of the differences, see the subsection "Challenges of nuclear-armed ICBMs versus conventionally armed shorter-range missiles" in Section 3: Challenges of Missile Defense.

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 also do not discuss North Korea's short-, medium– and intermediate-range missiles, which would chiefly be used in the Asia-Pacific region.

We do not consider missile defense systems intended to defend against the numerically larger and technically more sophisticated current and anticipated nuclear-armed ICBM forces of Russia or China. These forces are likely to include delivery systems that use technologies specifically designed to evade 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; Sonne 2019; Hyten 2020], the capabilities of the current U.S. systems are low and will likely remain low for the next 15 years. To focus our report further, we consider what would be required to defend the United States 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 and the 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 20 to 30 minutes for ICBM trajectories from North Korea to the continental United States.

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 true trajectories, which take into account the rotation of Earth.

- **Terminal phase.** The terminal phase begins once the warhead and the objects accompanying it re-enter the atmosphere at an altitude of about 100 km and begin slowing due to air resistance as the warhead descends toward its target. This phase lasts less than a minute.

The objective of a missile defense system is to disable the ICBM or its warhead during one of these three phases of flight, to prevent its warhead from damaging or destroying its intended target.

The weapons currently being proposed to disable North Korean ICBMs during their boost phase are airborne or space-based interceptors. (Here we use “interceptor” to refer to a booster rocket with a kill vehicle.) The proposed airborne interceptors would be based on long-duration 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 currently deployed U.S. midcourse warhead-intercept systems are the Ground-based Midcourse Defense (GMD), which has interceptors 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 has recently been 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) system was developed to defend against the warheads of shorter-range ballistic missiles, but there are recent 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 2019 U.S. Missile Defense Review [MDR 2019] called for further development and testing of all the missile defense elements mentioned above and more, and $10 billion or more has been allocated annually to the missile defense program in recent years. The Biden administration’s 2022 Missile Defense Review [MDR 2022] continues a firm commitment to defending the continental United States but narrows its programmatic focus to improving the capabilities of the GMD system. It does not mention use of Aegis, THAAD, or possible boost-phase intercept systems for defending the United States.

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.

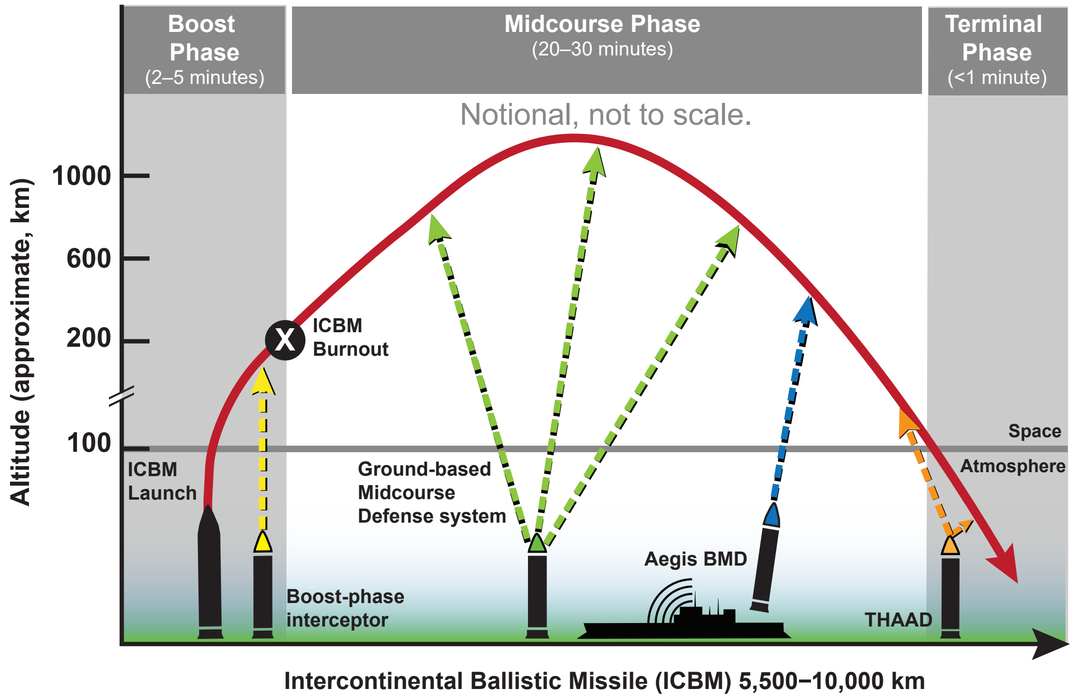

Figure 2 Schematic portrayal of the layered missile defense system being proposed to defend the United States against ICBMs launched from North Korea. An attempt can be made to intercept an ICBM while its rocket engine is burning (its boost phase), during the flight of its warhead through the vacuum 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 continental United States 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.)

We do not consider many other important questions related to missile defenses, such as the appropriate level of funding for missile defenses 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 2023]. 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 1910–1945 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 North Korea on a path to obtaining nuclear weapons 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. U.S. missile defense capabilities are just one component of this complex question.

The next two sections describe North Korea's current ICBMs and nuclear warheads, and some of the key challenges that confront efforts to build a system that could defend the United States against these ICBMs once they are launched. The two main sections of the report then follow. The first describes midcourse warhead-intercept systems, including the GMD system and potential contributions of the regional Aegis BMD and THAAD systems, while the second describes boost-phase missile-intercept systems, including possible land-, sea-, air-, and space-based rocket interceptors and aircraft-based 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. continental United States against the limited offensive missile threats posed by states such as North Korea.

The 2022 Missile Defense Review [MDR 2022] indicates that while the current long- range U.S. missile defense system is still intended to address offensive missile threats from North Korea and potentially from Iran, its goals are more modest than a robust defense and include "reassuring Allies and partners that the United States will not be coerced by threats to the homeland," "denying an aggressor the ability to execute small-scale coercive nuclear attacks or demonstrations," "complicat[ing] adversary decision-making by injecting doubt and uncertainty about the likelihood of a successful offensive missile attack," and "mitigat[ing] damage to the homeland and help[ing] protect the U.S. population" should deterrence fail (p. 6).

This report's focus on North Korea's nuclear-armed ICBMs is consistent with the assessment [Van Diepen 2023c] that North Korea is unlikely to deploy intercontinental-range submarine-based ballistic missiles that could strike the continental United States within the 15-year time horizon of this study.

The United States relies on nuclear deterrence to deter attacks from any source, including North Korea [MDR 2022, 6–7].

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 2024], 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 2022 Missile Defense Review, which states [MDR 2022, 5], "To address intercontinental-range, nuclear threats from Russia and the PRC, the United States will continue to rely on strategic deterrence—underwritten by safe, secure, and effective nuclear forces— to deter such threats," and with the fiscal year 2020 (FY 20) National Defense Authorization Act, which says [NDAA 2020, 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

As we describe below, North Korea has tested at least four types of ICBMs capable of striking part or all of the continental United States: its liquid-propellant Hwasong-14 (U.S. designation KN-20), Hwasong-15 (KN-22), and Hwasong-17 (KN-28), and its solid-propellant Hwasong-18 [CRS 2023].

Liquid-propellant ICBMs.
North Korea successfully tested its first ICBM, the two-stage, liquid-propellant, road-mobile Hwasong-14 (U.S. designation KN-20), on July 4 and July 28, 2017 [CSIS 2024a]. Initially it was assumed to have a range of at least 10,000 km and hence the ability to deliver a warhead to a target anywhere in the United States [Hanham 2017; Panda 2017b; CSIS 2022b; BBC 2023]. Subsequent analyses of open-source data on the tests led to revised assessments that it may only be capable of lofting a 500–600 kg payload a distance of 6,000 to 8,000 km [Postol 2017; Schilling 2017; Wright 2017a; Acton 2018; Elleman 2018]. if so, the Hwasong-14 could deliver a warhead of this mass to targets in Alaska and Hawaii, and perhaps to Seattle, but not to targets further east.

North Korea successfully tested a longer-range, two-stage, liquid-propellant, road-mobile ICBM, the Hwasong-15 (KN-22), on November 28, 2017. It may have successfully flight tested a variant of this missile in March 2022 [CSIS 2024b] (but see [Van Diepen 2022a]). North Korea successfully flight tested the Hwasong-15 a second time on February 18, 2023 [CSIS 2024b]. It tested a Hwasong-15 variant on November 3, 2022, which failed during second-stage flight [Van Diepen 2022c]. The Hwasong-15 has probably been operationally deployed since 2017 [Van Diepen 2022c; CSIS 2024b].

The Hwasong-15 is estimated to have a full burn time of 289 seconds, a maximum range of about 13 ,000 km [Panda 2017 b;Dominguez 2019; Bennett 2021; CSIS 2024b; DIA 2021, 24], and the ability to carry "penetration aids" (devices designed to enable the warheads to penetrate missile defense systems). If launched from any site in North Korea, it would be able to strike targets anywhere in the continental United States.

The Hwasong-15 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 two-stage, liquid-propellant, road-mobile ICBM that would be much larger than the Hwasong-15 [Van Diepen 2020; Varner 2020]. This missile was provisionally designated by observers as the Hwasong-16 (KN-27) and was initially assumed to be capable of delivering a payload of 2,000 to 3,500 kg, large enough to include several warheads, to any point in the continental United States [Davenport 2020; Van Diepen 2020; Kristensen 2021]. North Korea does not appear to have tested this ICBM.

In February, March, and November 2022 North Korea tested variants or stages of an even larger two-stage, liquid-propellant, road-mobile ICBM that has been officially designated the Hwasong-17 [van Diepen 2022c]. This missile appears to be related to the Hwasong-17 model that was displayed in October 2020 [Smith 2022b]. North Korea tested a version of the Hwasong-17 on March 16, 2022 [Smith 2023; Wonju 2023], but this missile failed in-flight [Van Diepen 2022b]. North Korea likely then successfully tested some version of the Hwasong-17 on March 24, 2022, though some observers have argued that this test used a version of the Hwasong-15 [Van Diepen 2022b]. North Korea successfully tested a version of this ICBM on November 18, 2022 [Smith 2022b; Van Diepen 2022b]. The Hwasong-17 has probably been operationally deployed since its successful November 2022 test [Van Diepen 2023a].

At present, less is publicly known about the Hwasong-17 than about North Korea's other ICBMs. According to Japanese Defense Minister Hamada, the version tested on November 18, 2022 has a maximum range of 15,000 km [Mackenzie 2022]. A missile of this size could deliver multiple warheads and penetration aids to targets anywhere in the continental United States [Van Diepen 2022b]. If it is able to do this, it could pose even more serious challenges to midcourse warhead-intercept missile defense systems (see "Midcourse Intercept Systems" below). Models of the Hwasong-17 based on photographic imagery indicate that it has a long total burn time of approximately 400 seconds [Brügge 2022; Brügge 2023]. If so, this would make it more vulnerable to boost-phase intercept defensive systems than the Hwasong-15 (see "Boost-Phase Intercept Systems" below).

Solid-propellant ICBMs.

In recent years, North Korea has been developing more advanced solid-propellant rocket motors and ballistic missiles that use them. In 2023, North Korea successfully tested and has now likely operationally deployed a solid-propellant ICBM capable of striking the continental United States [Van Diepen 2023e]. Solid-propellant missiles are easier to move and hide, and can be launched more quickly than liquid-propellant missiles, which need to be fueled before launch and cannot remain fueled for long periods of time.

In December 2022 North Korea announced that it had successfully carried out a static ground test of a large-diameter solid-rocket motor [Choe 2022; Van Diepen 2022d]. It had been working on this challenge for several years [Smith 2020]. North Korea claimed that this motor can generate 140 metric tonnes of thrust, sufficient to power the first stage of a solid-propellant ICBM, and that it has thrust-vector control [Van Diepen 2022d].

With this successful test of a large-diameter solid-rocket motor, North Korea demonstrated that it had overcome many of the technical challenges involved in scaling up solid-rocket motors to the sizes required for long-range ballistic missiles [Caveny 2003; Podvig 2004; Schiller 2019; Smith 2020] and knowledgeable observers suspected this solid-rocket motor was intended to be used in an ICBM [Choe 2022; Van Diepen 2022b].

At the beginning of 2023, North Korea's leader Kim Jong Un vowed to develop a new ICBM for "quick nuclear counter-strike" [Shin 2023]. North Korea then successfully flight-tested a three-stage, solid-propellant, road-mobile ICBM, designated the Hwasong-18, three times in 2023: on April 13 [Van Diepen 2023b], July 12 [Van Diepen 2023d], and December 18 [Van Diepen 2023e]. The Hwasong-18 is estimated to have an operational range of about 15,000 km, and is therefore capable of striking targets anywhere in the continental United States, depending on the weight of its payload [Van Diepen 2023e]. It is thought to have a full burn time of only about 170 seconds, much shorter than the full burn time of North Korea's liquid-propellant Hwasong-15, which—as noted above—is estimated to have a full burn time of 289 seconds.

As we explain below, in the section "Boost-Phase Intercept Systems", a boost-phase defense against solid-propellant missiles would be much more challenging, because they can be launched with less preparation time and have substantially shorter burn times than liquid-propellant missiles.

North Korea appears to have considered the Hwasong-18 as operationally deployed since its test on December 18, 2023 [Van Diepen 2023e]. It is expected to increase the overall size of North Korea's ICBM force, but will probably not replace the liquid-propellant Hwasong-15 and Hwasong-17 ICBMs [Van Diepen 2023e].

North Korea is also developing other solid-propellant ballistic missiles [Tong-Hyung 2023]. These include the two-stage missiles it tested on January 14, 2024 and April 2, 2024 [Abrams 2024; Tong-Hyung 2024; Xu 2024]. KCNA referred to the latter missile as a Hwasong-16B [Van Diepen 2024a; Zwirko 2024]. While the two-stage solid-propellant boosters used in both tests appear to be intermediate-range (IRBM) class missiles (commonly defined as missiles having a range of 3,000 to 5,500 km), which would allow them to strike U.S. bases in, for example, Guam [Abrams 2024;Van Diepen 2024a], some observers argue that their range is likely to be much less when they are armed with the hypersonic glide vehicles (HGVs) they carried in these tests [Xu 2024].

Launch platforms for ICBMs.

During the last several years, North Korea has made substantial progress in developing and testing a variety of launch platforms that could be used to transport and launch its ICBMs.

In his 2021 congressional testimony, then Director of the Defense Intelligence Agency Gen. Scott Berrier noted, "The October 2020 parade also featured eight road-mobile ICBM launchers, the most North Korea has ever displayed." [Berrier 2021] Imagery from North Korea's April 2022 military parade indicated that North Korea had acquired the ability to build road-mobile launchers for its ICBMs [Jewell 2022] and twelve road-mobile launchers for the Hwasong-17 ICBM were observed during a February 2023 parade in Pyongyang [Panda 2017b; Van Diepen 2023a; Ward 2017].

North Korea has also shown that it is developing the ability to launch missiles, likely including ICBMs, from trains [Bermudez 2021; Van Diepen 2021a; Smith 2021].

On September 15, 2021, North Korea for the first time launched short-range ballistic missiles (SRBMs) from railcars. This was significant for its first-time use of a rail launcher, not because of the missiles that were tested [Van Diepen 2021a]. The use of rail-mobile launchers to launch SRBMs was not as significant as the indication that North Korea may develop such launchers to launch ICBMs in the future. It is more difficult to make ICBMs road-mobile than smaller missiles, hence ICBMs would benefit much more from rail mobility. Although rail-mobile ICBMs would be less survivable than road-mobile ICBMs, they would be significantly more survivable than fixed-base ones [Van Diepen 2021a].

An unconfirmed August 2016 Radio Free Asia report extensively described both a different class of rail-mobile missile launcher (8-axle) than the one observed (4-axle) during the September 15 test launch, and a rail-mobile missile launcher potentially capable of transporting and launching ICBMs [Bermudez 2021].

The costs in manpower and other resources required to operate rail-mobile launch platforms for solid-propellant missiles are significantly lower than for comparable liquid-propellant missiles [Bermudez 2021].

This evidence suggests that North Korea may no longer be constrained by limits on its ability to produce launchers that can carry and launch ICBMs. It may therefore now be able to deploy 10 or more ICBMs on road- and rail-mobile launchers and launch them within a short period of time (a "salvo" launch). This would further challenge any missile defense.

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 2022] 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; Hecker 2021; Kristensen 2022; CRS 2023]. 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 2022]. 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; Kristensen 2022]. 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 ICBM and a re-entry vehicle robust enough to survive the rigors of launch and re-entry into the atmosphere after a full-range 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 2023]. A careful independent assessment [Wright 2017b] 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 does not 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].

Moreover, for some years North Korea has been developing technologies designed to give its warheads greater ability to penetrate missile defense systems. In 2019, it tested two solid-propellant, short-range missiles, the KN-23 and KN-24, which had warheads designed to perform low-altitude maneuvers intended to make them harder to intercept [CSIS 2024c; CSIS 2024d].

Beginning in 2021, North Korea began tests of longer-range missiles lofting conical or wedge-shaped warheads with hypersonic cross-range maneuvering capability [Xu 2024]. Warheads with this capability are usually referred to as hypersonic glide vehicles (HGVs) and are intended to evade missile defenses.

In September 2021, North Korea tested what it called its first hypersonic missile, the Hwasong-8, which had a wedge-shaped boost-glide warhead [Gallo 2021; Trevithick 2021; Xu 2024]. In an official statement, the South Korean Joint Chiefs of Staff said 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 missiles with conical-shaped HGVs [Rogoway 2022; Smith 2022a; Xu 2024]. It then tested a two-stage, solid-propellant missile with a conical-shaped HGV in January 2024 and a two-stage, solid-propellant missile with a wedge-shaped HGV in February 2024. The missile used in the February test is being referred to in English as the Hwasong-16B [Xu 2024].

North Korea's development and testing of these HGVs is motivated in part by their potential ability to evade missile defense systems. The development and testing of the very large Hwasong-17 ICBM is also likely motivated in part by its potential ability to carry and launch multiple warheads and missile defense penetration aids to counter U.S. missile defense systems [Van Diepen 2022b].

In a January 2021 speech, Kim Jong Un said that North Korea was working on the technology needed for a multi-warhead rocket [KCNA 2021]. Then, in June 2024, North Korea tested what it claimed was a missile with three independently guided warheads and a decoy [Feng 2024; Gallo 2024; Kim 2024]. Although video of the test released by the Republic of Korea's military indicated that it probably failed, this test shows that North Korea is committed to developing multiple-warhead missiles and decoys, and may be seeking to develop multiple independently targeted re-entry vehicles (MIRVs) [Van Diepen 2024b].

These tests demonstrate that North Korea is continuing to devote substantial resources to developing countermeasures to missile defenses.

THE NORTH KOREAN ICBMs WE CONSIDER

Based on the information presented above, North Korea probably currently has more than a dozen liquid-propellant ICBMs that could strike targets in part or all of the continental United States. These are its Hwasong-14,-15, and -17 ICBMs. It has road-mobile launchers for these ICBMs and is working on rail cars to launch missiles from trains.

North Korea's Hwasong-15 is more capable than its Hwasong-14 and appears to be a more significant element of its current ICBM force than the Hwasong-14. Its much larger Hwasong-17 has the potential to be much more challenging to some missile defense systems than the Hwasong-15. However, not enough is currently publicly known about the characteristics and performance of the Hwasong-17 for us to be able to model it adequately. We therefore chose to use a model of the Hwasong-15 to illustrate the threat posed by North Korea's liquid-propellant ICBMs.

North Korea's Hwasong-18 solid-propellant ICBM also appears to be a significant element of its current ICBM force. The Hwasong-18 poses special challenges for any U.S. missile defense system, but particularly for a boost-phase intercept system. We therefore chose to use a model of the Hwasong-18 to illustrate the threat posed by a solid-propellant ICBM.

The accuracy of North Korea's ICBMs is likely to be low and their reliability has not been demonstrated. They would therefore likely be used against relatively large, less time-urgent targets such as cities, rather than against hardened military targets.

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 warheads would fly if used to attack the United States, but there appears to be no technical barrier to its building them.

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 glider-like warheads. It has not yet demonstrated these countermeasures and warheads in tests of long-range missiles. Its purpose in developing the very large Hwasong-17 ICBM is probably to carry multiple warheads and penetration aids to overcome missile defenses.

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 solid-propellant ICBM like the Hwasong-18, or a salvo launch of 10 such ICBMs at intervals of less than a minute.

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 to effectively remedy problems identified in the large and complex U.S. missile defense program.

TECHNICAL CHALLENGES OF ICBM INTERCEPT

For systems intended to intercept ICBMs or their warheads, the brevity of the missile's boost phase, the lack of drag on the warhead during the midcourse phase of its flight, and the brevity of the warhead's reentry phase pose daunting technical challenges to defensive systems. But "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).

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. To be secure, interceptor bases and aircraft must be positioned at least 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 the ships carrying the interceptors are beyond the horizons of land-based radars and have adequate room to maneuver (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 instead a large enough number of rocket interceptors were 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 or even thousands of interceptors in low-Earth orbit would be required to make sure that one is within range at all times to defend against even a single ICBM launched from a single site. Moreover, there are a variety of potentially effective countermeasures to boost-phase intercept, such as launching several ICBMs nearly simultaneously (a "salvo" launch) or programming evasive maneuvers by the ICBMs.

The midcourse phase of flight, during which the ICBM's nuclear warhead(s) follow ballistic trajectories, lasts about 20 to 30 minutes. The absence of air drag during this phase means that launch debris, such as spent upper stages, deployment and attitude control modules, separation debris and debris from unburned fuel, insulation, and other parts of the booster, as well as missile fragments deliberately created by the offense and light-weight decoys and other penetration aids, 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 it can target the warhead. Furthermore, 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 of a nuclear warhead.

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 fired from bases close to the warhead's target could reach and disable a warhead during the terminal phase of its flight before it detonates. Lightweight decoys accompanying the warhead would be stripped away by the atmosphere only during the final 10 seconds or so before the warhead explodes. Hence even effective terminal-phase defenses can defend only limited areas, such as a metropolitan area or a critical military facility or command post. Moreover, terminal-phase sensors are vulnerable to the blinding effects of nuclear explosions in the atmosphere.

Given all these challenges to ballistic missile defenses, it is easy to understand why, when engineers have been under intense political pressure to deploy a system, the United States has repeatedly initiated 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 $400 billion in 2020 dollars [BMD Expenditures 2021] since 1957 on research, development, and deployment of ballistic missile defense systems, none of which have proven effective.

CHALLENGES OF NUCLEAR-ARMED ICBMS VERSUS CONVENTIONALLY ARMED SHORTER-RANGE MISSILES

The argument has sometimes been made that an effective defense against nuclear-armed ICBMs must be feasible because of early claims of successful intercepts of conventionally-armed shorter-range missiles by the United States' Patriot system and Israel's Iron Dome. This argument is again being made based on recent reports of successful intercepts of conventionally armed, shorter-range rockets and missiles by newer systems, such as Israel's David's Sling, Arrow-2, and Arrow-3, and the United States' SM-3. As we now explain, none of these systems has been fully successful in defending against even shorter-range, conventionally armed rockets and missiles, and defending against nuclear-armed, intercontinental-range missiles is a far greater challenge, both because intercepting an ICBM or its warhead is much more difficult and because the consequences of even a single nuclear warhead reaching its target and exploding would be catastrophic.

Development of the Iron Dome system began about fifteen years ago to defend against artillery and 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 only 4 – 70 km [Lister 2021]. They do not strike incoming rockets but instead try to approach them and then explode, sending out shrapnel that can disable a home-made rocket 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. Even so, it is now claimed to disable about 80% – 90% of the rockets it engages, or about 40% – 45% of the rockets launched against the area it is defending [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" [Hearings 1992]. (For further details, see [Lewis 1993; Sullivan 1999].)

In 2015, 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 Patriot system failed when confronting a missile much less capable than an ICBM [Fisher 2017].

A more recent example useful for understanding the challenge posed by nuclear-armed ICBMs is the defense mounted against the April 13, 2024 conventional missile attack by Iran on Israel. In that attack, Iran reportedly launched about 170 slow-flying, low-altitude drones, about 30 cruise missiles, and about 120 short-and medium-range ballistic missiles [George 2024; Spender 2024; Thomas 2024]. Iran gave advance warning of the attack, which allowed Israel, the United States, France, the UK, and Jordan to activate a large network of sophisticated sensors and defensive weapon systems [Balzer 2024; George 2024; Lagrone 2024; Lendon 2024; Spender 2024].

The drones, which were slow and carried relatively small munitions, either failed or were shot down by fighter aircraft before reaching Israeli airspace, and the cruise missiles, which likewise either failed or were intercepted [Barrett 2024; Mongilio 2024; Spender 2024], are not relevant to our discussion of defenses against ballistic missiles.

About 50% of the ballistic missiles reportedly either failed at launch or in flight [Spender 2024]. Hence about 60 continued toward their targets. About ten warheads struck their targets, which included two air bases and a radar site [Kasapoğlu 2024; Lendon 2024; Lewis 2024; Spender 2024]. The damage they caused was minimal, largely because air bases are relatively hard targets [Kasapoğlu 2024; Lewis 2024]. Perhaps another ten may have landed too far from their targets to be counted [Lewis 2024]. This suggests that the combined missile defense systems of Israel and the United States were able to intercept 60% to 80% of the incoming medium-range ballistic missiles [Lewis 2024]. While this was a large enough percentage to be labeled a success in this situation, if any of these missiles had been aimed at cities instead of air bases and if even one of them had been carrying a nuclear weapon, reached its target, and exploded, it would have been a catastrophe.

Unlike the interceptors of any systems designed to defend against ICBM warheads, the interceptors of Israel's Iron Dome, David's Sling, and Arrow-2 and the U.S. Patriot system are designed to intercept missiles within the atmosphere, where as noted above, lightweight decoys and other penetration aids cannot be used to fool the defensive system.

In contrast to the missiles we have been discussing, which traveled about 1,000 km at speeds of about 3 km/s, the ICBM warheads the GMD system would have to intercept would be traversing distances of 10,000 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. Moreover, if the GMD system were to miss the nuclear warhead it was seeking to destroy, the warhead could explode on its target with a power a million times greater than the warheads that Israel's Iron Dome, David's Sling, and Arrow-2 systems, and the United States' Patriot system, sometimes miss, and would utterly destroy its target and the surrounding area.

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 and the offensive system adaptations required to evade 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 enormously 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 weapons 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 accelerates 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. Russia's 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 Department of Defense (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 MaRVs [maneuvering re-entry vehicles], MIRVs [multiple independently-targeted re-entry vehicles], decoys, chaff, jamming, thermal shielding, and hypersonic glide vehicles" [DOD 2019]. In summer 2021, China reportedly tested a system that placed a maneuvering glide vehicle on 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 evade. 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" [JASON 2010].

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. The 2012 National Academies report [NRC 2012] 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). 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 their midcourse flight. Currently, the sole system deployed to defend the continental United States against an ICBM attack is the Ground-based Midcourse Defense (GMD) system. To increase the overall effectiveness of this system, in 2020 the Missile Defense Agency proposed a "layered" approach in which attempts to intercept ICBM warheads during their midcourse phase of flight 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 their midcourse phase and, perhaps finally, a system based on the Army's THAAD system during their terminal phase (see Figure 2).

The development of a missile defense system to defend the continental United States against an ICBM attack 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 U.S. midcourse warhead-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 warhead-intercept systems, including potential countermeasures and their possible remedies, and the three elements of the layered approach that has been 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 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 about 20 to 30 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]. Thus, the UHF radars, such as the Upgraded Early Warning radars the GMD system relies on for tracking, would be unable to track objects in or behind such an ionized cloud. Because attenuation scales with the inverse square of the frequency, the higher-frequency S- and X-band (2–4 and 8– 12 GHz) forward-based and discrimination radars may be able to track objects in the threat cloud [Canavan 2003, Fig. D.1] during parts of their trajectories. However, fluctuations in the radar signatures of the warhead and other objects would make discrimination significantly more difficult under these conditions, even for the S- and X-band radars.

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 system's 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 from other objects in the threat cloud.

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.

The new GMD interceptor design, the Next Generation Interceptor, will carry multiple kill vehicles, which will increase the number of targets that could be intercepted, as could inclusion of Aegis Standard Missile-3 (SM-3) IIA interceptors in the midcourse defense system. But a shoot-look-shoot strategy provides little advantage if the warhead cannot be discriminated from numerous decoys.

Proposed midcourse warhead-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 2017 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 complex 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 track and discriminate objects in the threat cloud. 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 objects in the threat cloud is poor.

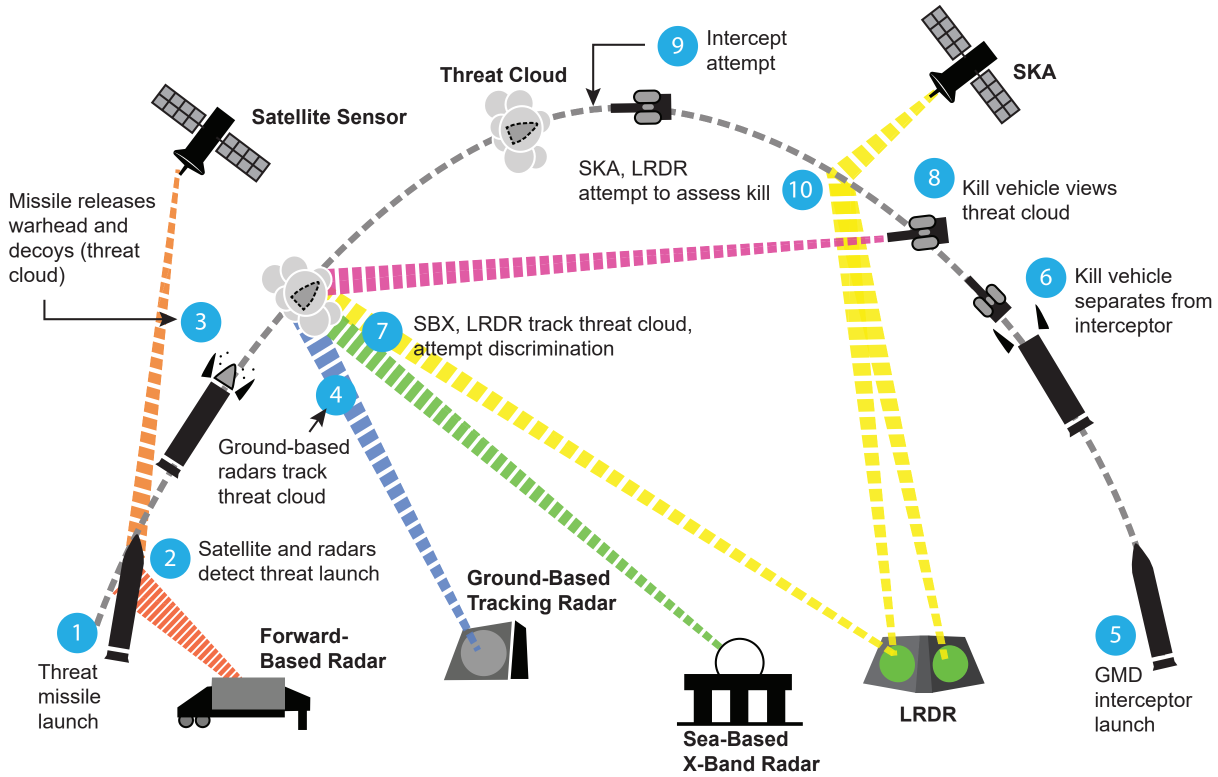

Figure 3 Sequence of events in an attempted warhead intercept by the GMD system. The launch of a threatening ICBM from North Korea (1) is detected within a minute by forward-based radars and satellite-based infrared sensors (2). At the end of the boost phase, the ICBM deploys its warhead and decoys (3) The warhead, decoys, and any other accompanying objects that must be discriminated from the warhead are referred to as the "threat cloud." In this example, a balloon encloses the warhead and other similar balloons are decoys. 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].

THE 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 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 deploy a system to be able to defend against missiles that North Korea, Iran, and Iraq might field [Bush 2002]. It therefore accelerated 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" requirement was created, allowing the GMD to be fielded without the normal 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-wave-length 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 fired 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 2024]). 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), had two competing bidders who were selected to develop and build prototype interceptors, with Lockheed Martin selected in April 2024 as the sole contractor going forward with an expected initial operational capability in 2028. 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 the 44 existing GBIs. starting in 2027 at the earliest, and potentially replace them in the future [MDR 2022, p. 6]. Importantly, few spares of the currently deployed interceptors are available for tests.

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 more sensitive 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 Hawaii, and the S-band Long-Range Discrimination Radar (LRDR) in Clear, Alaska, which is expected to become operational in December 2024. 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 6]. 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 [NRC 2012, 75]. 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 ICBMs 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 Hawaii 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]. In 2023, the DOD stated that it was not moving forward with the Hawaii radar and it appears that the focus will shift to new sensors in space [Liang 2023].

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: the Pentagon has consistently rated the GMD tests as low in operational realism. Even so, the system has failed as often as it has succeeded. Of the 20 tests conducted since 1999, the interceptors successfully destroyed their targets 11 times [GMD Tests 2024].

Realism would require testing against threat-representative targets that include complex countermeasures and with unannounced target launch times [DOT&E 2015]. But only two tests have used simulated warheads of ICBM-range missiles as targets, and in all the successful intercept tests, the time of the test was chosen so 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 [APS 2003, Sec. 3.3; NRC 2012, 134].

The GMD's slow pace of testing—only 20 intercept tests in 25 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 credible message to the international community on our ability to defeat missiles in all phases of flight, thus reducing their value to potential adversaries" [MDA 2024]. The tests are also expensive, costing $200 million to $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 objects in the threat cloud.

The DOD apparently judged it infeasible to start over and instead continues to plan incremental improvements, such as refurbishing existing interceptors and adding the ability to fire only two of the three boost stages before deploying the kill vehicle, 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, and it has limited 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 fired 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, "the GMD weapon system has demonstrated the capability to defend the U.S. homeland from a small number of ballistic missile threats employing simple countermeasures and with ranges greater than 3,000 kilometers" [DOT&E 2024, 340].

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 Hawaii). 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 2024b]. 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 Hawaii 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 fired 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 continental United States 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 2024b, 19–21]).

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 40–50 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 could be conducted against ICBM warheads, the system will would need crucial upgrades that, among other things, would significantly increase the speed of its interceptor and double its range [Sherman 2020]. 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 planned to have 60 Aegis BMD-capable ships by the end of FY23 [MDR 2019, 48] that could host scores to hundreds of SM-3 IIA interceptors. The GMD and Aegis interceptor inventory would 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 112 mobile ICBMs [Kristensen 2023], 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 2022]. 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 [APS 2003; Wilkening 2004] 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 [NRC 2012] concluded, "With one or two minor exceptions, land-, sea-, or air-based boost-phase defense is not feasible when timeline, range, geographical/geopolitical, or cost constraints are taken into account" [NRC 2012, 8]. It also found that the total life-cycle cost of deploying 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, 9]. Consequently, the first major recommendation of the 2012 National Academies report 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, 15].

While the 2022 Missile Defense Review does not mention boost-phase missile defense at all [MDR 2022], numerous 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, have recently been 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].

The 2023 NDAA mandated a study of space-based missile defense by an appropriate federally funded research and development center that is certain to consider a system that has boost-phase intercept as its sole purpose or both boost-phase and midcourse intercept as its purpose [NDAA 2023, Sec. 1671].

Boost-phase intercept of ICBMs launched from even a small country like North Korea is challenging. To be reliable and effective, a boost-phase missile defense 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.

We note that ICBMs launched from many locations in 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 missile defense system would have to launch at least several, and perhaps dozens of interceptor missiles over Chinese territory, and their final stages and any kill vehicles that missed their targets would come down in China or Russia. Hence the consequences of firing such a system by mistake could be very serious. Such a missile defense 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.

In this chapter we reexamine this type of missile defense system 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 challenges faced by boost-phase missile defense systems that would use land-, sea-, or air-based rocket interceptors to defend against North Korean ICBMs have become even more difficult than they were at the time of the 2012 National Academies Study.

Significant developments include some new proposals for drone-based boost-phase interceptors (Garwin 2018a; Goodby 2018; cf. Wells 2024]). Also, as described in the earlier chapter on North Korea's ICBM capabilities, North Korea has now successfully tested and deployed its Hwasong-15 liquid-propellant ICBM, which has a total burn time 20% longer than the total burn times of the hypothetical liquid-propellant ICBMs considered in the 2003 APS and 2012 National Academies studies. As a result, the Hwasong-15 would be modestly more vulnerable to boost-phase intercept in some circumstances than the hypothetical liquid-propellant ICBMs considered in these studies.

But North Korea has also now successfully tested and likely deployed its Hwasong-18, a solid-propellant ICBM that has a much shorter total burn time than its liquid-propellant ICBMs. As a result, the boost-phase intercept systems that have been proposed using land-, sea-, or air-based rocket interceptors would have little or no ability to defend the entire continental United States against this ICBM.

Assuming interceptors would be fired almost automatically, the number required for a space-based interceptor system to be able to defend in principle against a single Hwasong-15 is at least 400, and about 4,000 would be required to defend against a salvo launch of 10 such ICBMs. The number of interceptors required for such a system to be able to defend in principle against a single Hwasong-18 is at least 1,600, and about 16,000 would be required to defend against a salvo launch of 10 such ICBMs. (We also 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 2024].)

Current and potential future circumstances therefore remain unfavorable for a space-based missile defense system. 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.

Solutions to other challenges faced by any boost-phase intercept system, such as possible countermeasures and the plume-to-hardbody handover and final homing problems, have not yet been demonstrated.

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 their midcourse or terminal phases of flight [APS 2003, S2 and Sec. 2.1].

Key challenges of boost-phase intercept.
In order to successfully defend against an attack by an ICBM, a boost-phase intercept system must be able to successfully and simultaneously deal with a number of challenging problems for which solutions have not yet been demonstrated. Crucially, the system must have interceptors able to reach the target ICBM before the ICBM has deployed its warhead(s) (the "reach-versus-time" challenge) and disable its final stage while it is in powered flight.

Meeting this challenge requires a system with interceptors that can reach the ICBM within about two to four minutes after it has been launched. To do this, the system must have remote sensors that can detect the launch of any threatening ICBM, estimate its trajectory, compute a firing solution for its interceptors, and fire its interceptors less than a minute after the launch of the ICBM has been confirmed by remote sensors. During their flight, the system's interceptors must be capable of using information from off-board and on-board sensors to successfully steer toward the predicted ICBM intercept point.

In addition to having interceptors that can meet the reach-versus-time challenge, to be successful a boost-phase defense must also meet other requirements. Its interceptors must be able to be based in locations that are geographically and geopolitically feasible and secure, which typically limits their capabilities. If the interceptors are fired from sea- or air-based platforms, these platforms must have the mass and space capacity to carry interceptors with the required performance.

The kill vehicle carried by the interceptors must be capable of using information from off-board and on-board sensors and have sufficient thrust for a sufficient time to successfully home on, hit, and disable the final stage of the ICBM while it is still in powered flight.

Finally, the system must have a sufficient number of interceptors to cope with the threat and a concept of operations that will make the system successful.

Analyzing such a complex system with so many elements is beyond the scope of this report (but see [APS 2003; Wilkening 2004; NRC 2012]).

In this report we focus on the reach-versus-time challenge, because a system that cannot meet this challenge cannot be successful. We illustrate this challenge by analyzing the performance a boost-phase intercept missile defense system would need to defend two example cities in the continental United States against an attack by models of North Korea's Hwasong-15 and Hwasong-18 ICBMs using two different examples of interceptors.

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 at least approximately; and they must reach the ICBM early enough to prevent its warhead from reaching the target.

It is difficult even for fast interceptors to achieve this. Whether it is possible depends on many factors. These include details of the offensive system, such as where the ICBM is based and how long its powered flight lasts—the total "burn time" of its boost phase, which depends strongly on whether it is a liquid- or solid-propellant ICBM—and the intended target. These factors also include the detailed capabilities of the defensive system, such as the speed of its interceptors, whether they are 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 the APS 2003 report [APS 2003], i.e., to refer to any additional time after the ICBM's trajectory is first estimated that can be used to evaluate whether a reported launch detection is an ICBM, a different type of missile, or a spoof; to resolve any uncertainties about the current performance of the defensive system; and to better identify the type of missile detected, its likely performance, and its trajectory [APS 2003, xxiii, S70].)

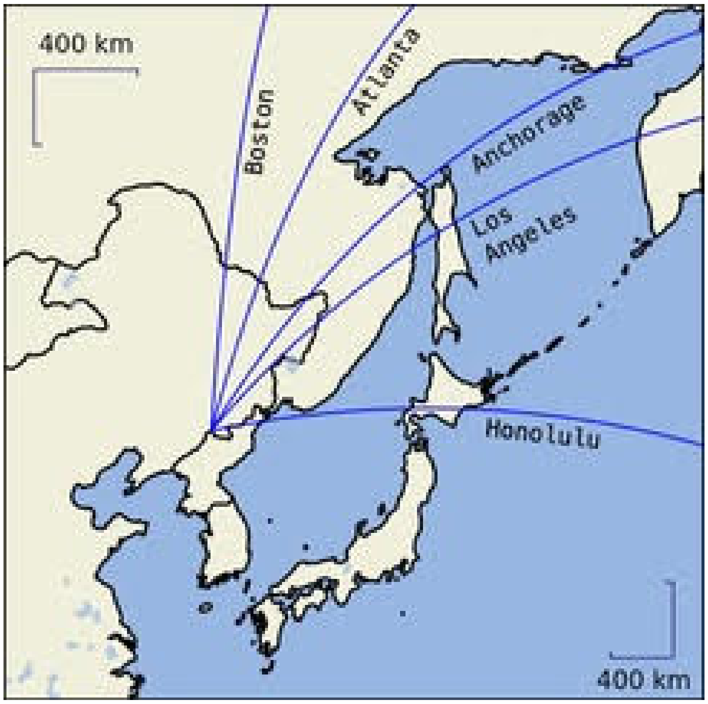

Figure 4 Map showing North Korea and adjacent countries and the initial ground tracks of ICBMs launched from north-central North Korea to five cities in the United States. ICBM ground tracks differ from great circles connecting the launch site to the target because of Earth's rotation. Cf. [APS 2003, Fig. 5.8].

To illustrate the reach-versus-time challenge, we chose a fictitious ICBM launch site in north-central North Korea, near Chunggang-up. This site is about 1 km from North Korea's border with China and happens to be not far from the Hoejung-ni Missile Operating Base that will likely house a regiment-sized unit equipped with ICBMs [CSIS 2022a].

Figure 4 shows a map of North Korea and the adjacent parts of China and Russia with the initial ground tracks of ICBMs launched from the fictitious ICBM launch site toward the five cities in the United States indicated. Our maps use the pseudo-cylindrical, or Robinson projection. The initial azimuths of these tracks are more westerly than the initial azimuths of the great circles connecting the launch site to the target cities because of the effects of Earth's rotation.

To illustrate the challenges of boost-phase intercept we chose as targets Boston and Los Angeles, which represent, respectively, one of the most challenging targets to defend against attacks by North Korean ICBMs and a target that is easier to defend.

If interceptors are based on or over the Yellow Sea or the East Sea/Sea of Japan, or in South Korea, Figure 4 shows that in order to intercept North Korean ICBMs headed to targets in the continental United States, the interceptors would have to overtake the ICBMs from behind, making interception during their boost phase challenging. If instead interceptors could be based in or over China or Russia, intercepting North Korean ICBMs headed toward the United States would be much less challenging, because they would then be heading toward the interceptors' basing locations. But 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, 15, footnote 13].

Interceptor basing areas.
For a given ICBM trajectory and intercept time, the kinematically allowed basing area for a given interceptor and interceptor firing time is a circular area on the ground centered directly under the point where the ICBM will be when it is intercepted. The radius of this area is approximately equal to the horizontal distance the interceptor travels on its trajectory from the time it is fired until the time it intercepts the ICBM. This interceptor could reach the assumed intercept point at the assumed intercept time if it is based anywhere within the kinematically allowed basing area and is fired at the appropriate time. (See [APS 2003, Sec. 4.6] for a more precise definition and further discussion of the kinematically allowed interceptor basing area.)

For the same interceptor firing time but a later intercept time, the kinematically allowed basing area would be centered farther along the ICBM's trajectory and have a larger radius. The kinematically allowed basing area would be largest if the ICBM could be intercepted just before it gives its warhead the velocity needed to reach its intended target [APS 2003, Ch. 5], but the intended target is generally not known in advance by the defense.

Some locations within the kinematically allowed basing area may be unavailable or unsafe places to base interceptors. For a given ICBM trajectory and intercept time, the possible basing area for a given interceptor and interceptor firing time is that portion of the kinematically allowed basing area, if any, where interceptors can safely be positioned or adequately defended.

The possible interceptor basing areas for defending against ICBMs launched from North Korea depend on many factors that are currently unknown and some that are likely to be unknown even at the time of any attack. These include the ICBM launch sites used, the types of ICBMs used and their precise performance characteristics, the intended targets, and the flight paths the ICBMs are programmed to fly to their targets. Also important are the altitude at which the interceptors are fired, their performance, and the defense's concept of operations, including whether any decision time is allowed and whether multiple interceptors will be fired against each ICBM. This report illustrates the effects on the size and location of the possible interceptor basing areas of several of the most important factors.

To illustrate the roles of these factors, we use models of two of North Korea's ICBMs and two interceptors. The parameters that determine the performance of these ICBM and interceptor models are listed and discussed in the Technical Supplement that accompanies this report and in [Wells 2024]. The results we show for these models are from [Wells 2024].

The two ICBMs we consider are North Korea's liquid-propellant Hwasong-15 and its solid-propellant Hwasong-18 (see Section 2: North Korea's ICBM Capabilities). As noted above, we assume the ICBMs are launched from a site in north-central North Korea that favors the offense.

The two interceptor models we use have burnout velocities of 4 km/s and 5 km/s, respectively, when they are fired vertically from an altitude of 15 km and the effects of gravity and atmospheric drag are included. We have chosen to illustrate the effect of the interceptor's burnout velocity on the performance of the defensive system using these two values for their burnout velocities because these are similar to the burnout velocities of the sea- and air-based interceptors considered in previous work (see [APS 2003; Wilkening 2004; NRC 2012; Garwin 2018a; Goodby 2018; Wells 2024]).

The performance of a given interceptor depends on the altitude at which it is fired primarily because the atmospheric drag on an interceptor fired from Earth's surface is greater than the drag on an interceptor fired from a high altitude. A launch altitude of 15 km is appropriate for drone-based interceptors [Wilkening 2004; Garwin 2018a; Wells 2024]. To achieve the same burnout velocity when fired from the ground or from ships at sea, the interceptors would have to be more capable and hence larger and heavier. This is typically not an important consideration for land-based interceptors but is important for interceptors based on ships. In the discussion below we note when the physical size of the interceptor is an important consideration.

Figure 5 below illustrates the boost-phase intercept reach-versus-time challenge for our model ICBMs and interceptors. The kinematically allowed basing areas shown in this figure are from [Wells 2024]. They make some of the same assumptions that were adopted in the 2003 APS report [APS 2003, xxvi]. For example, they assume that the defensive system has modern missile detection and tracking capabilities. But they also assume that the system's interceptors are fired at the earliest moment a firing solution can be constructed.

A firing solution cannot be constructed immediately after an ICBM is launched. When a firing solution 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], Sec. 2.4.1).

With modern sensors, an interceptor firing solution for a liquid-propellant ICBM like the Hwasong-15 is expected to become available about 65 seconds after the ICBM has been launched, about 20 seconds after the launch has first been detected by remote sensors. For a solid-propellant ICBM like the Hwasong-18, a firing solution is expected to become available about 45 seconds after it has been launched, about 15 seconds after the launch has first been detected. (For details, see [APS 2003, Secs. 2.2, 2.4.1, 12, and 14, and Appendices B and C; NRC 2012, Fig. 2–3].)

The 2012 National Academies study found it counterproductive to commit an interceptor earlier than these times [NRC 2012, 64, footnote 33]. Even committing interceptors at these times means they must be fired almost automatically, i.e., with no decision time.

That all these times are so short reflects the reach-versus-time challenge intrinsic to boost-phase intercept [NRC 2012, 15; Wells 2024]. The time available might be increased if distributed or improved sensors and machine learning allow as-yet-unquantified improvements in estimating the trajectory of the target ICBM quickly and deciding whether to fire interceptors.

Defending against the Hwasong-15.

With our model, intercepting a Hwasong-15 ICBM launched from a site in north-central North Korea no later than about 260 seconds after it was launched would prevent its warhead(s) from striking cities in Alaska, in the northeastern United States, or on the U.S. West Coast (see [Wells 2024]).

Intercepting the ICBM this early would also eliminate the possibility that it could perform a dog-leg maneuver to strike a city in Alaska rather than a city in the northeastern United States, sacrificing range to have a better chance of evading a boost-phase missile defense system (see [APS 2003, Sec. 15.2; Wells 2024]). ("Dog-legs" are maneuvers in which the ICBM starts out in one direction and then veers off in another, making it difficult for the missile defense system to anticipate the trajectory of the ICBM's final stage.) Intercepting the Hwasong-15 later than 260 seconds after launch would benefit the defense little, because the interceptor is chasing the accelerating Hwasong-15 from behind and the Hwasong-15 is moving rapidly inland, away from safe interceptor basing areas [Wells 2024].

Figure 5(a) shows the kinematically allowed basing areas from which our model interceptors, which can rapidly accelerate to 4 km/s and 5 km/s, could reach our model of the Hwasong-15 ICBM launched from north-central North Korea in the direction of Boston (blue circles) or the direction of Los Angeles (orange circles), 260 seconds after it was launched. The smaller circles show the kinematically allowed basing areas for a 4 km/s interceptor; the larger circles show the kinematically allowed basing areas for a 5 km/s interceptor.

The constraints on possible basing areas shown by the wavy red lines in Figure 5(a), which are 100 and 200 km off the eastern coasts of North Korea and Russia, indicate distances beyond which interceptors could be safe while they are on station, depending on the capabilities

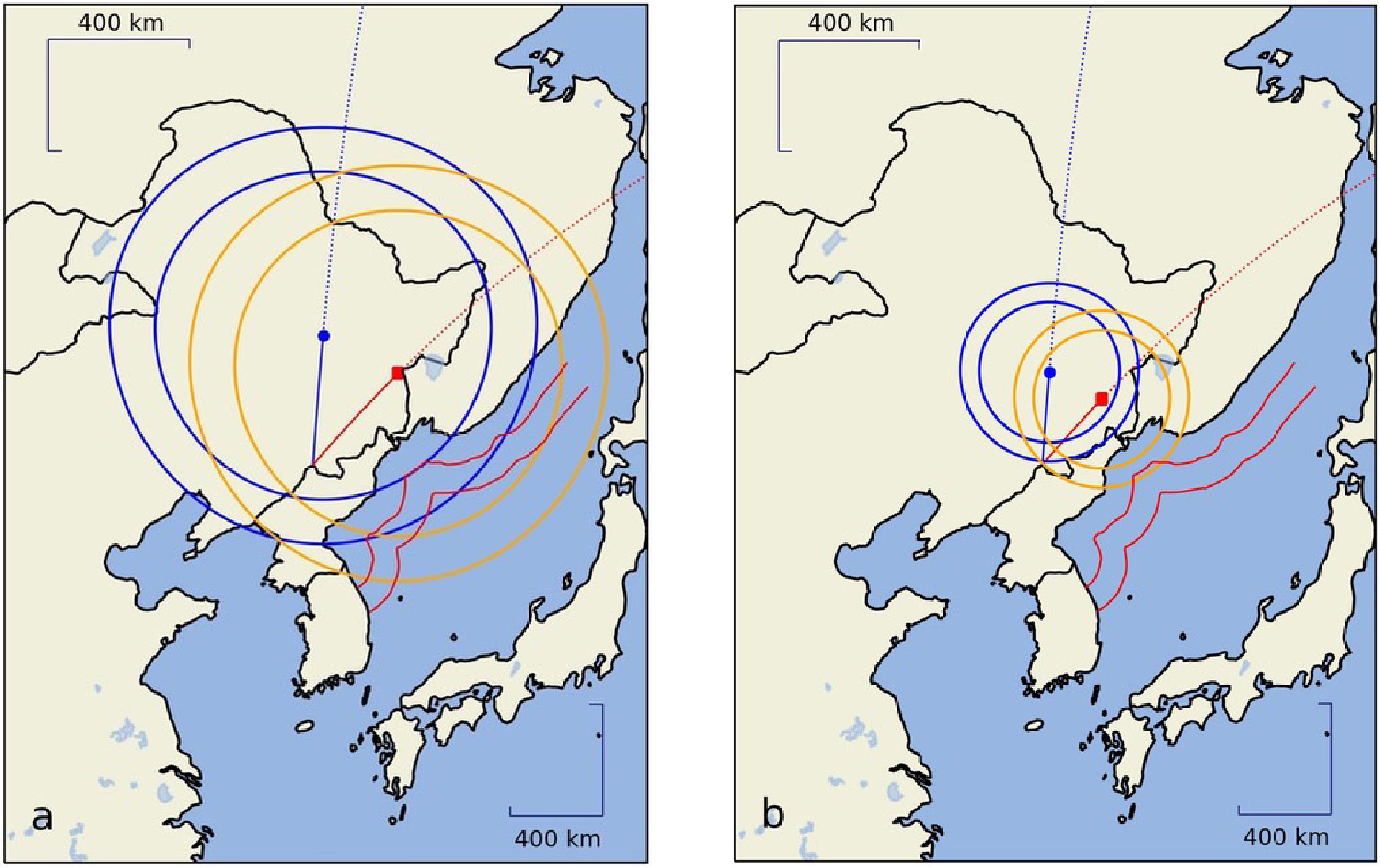

Figure 5 Basing areas that would allow the model interceptors discussed in the text to reach (a) the model of the liquid-propellant Hwasong-15 and (b) the model of the solid-propellant Hwasong-18 we used in time to prevent their warheads from striking targets in the continental United States, if they were launched from a site in north-central North Korea headed toward Boston or Los Angeles (see text for details). The model of the Hwasong-15 would have to be intercepted about 260 seconds after launch to defend the entire continental United States, whereas the model of the solid-propellant Hwasong-18 would have to be intercepted no later than 145 seconds after launch to do so. The slightly curved lines indicate the ICBM ground tracks from the launch site to the intercept points, which are indicated by a blue dot on the ground track for the Boston trajectory and an orange square on the ground track for the Los Angeles trajectory. The blue lines and circles are for ICBMs headed toward Boston; the orange lines and circles are for ICBMs headed toward Los Angeles. The smaller and larger circles indicate the kinematically allowed basing areas for interceptors with 4 km/s and 5 km/s burnout velocities, respectively. Both sets of basing circles assume the interceptors are fired as soon as a firing solution is available (zero decision time). The wavy red lines 100 and 200 km off the eastern coasts of North Korea and Russia indicate the distances beyond which on-station sea- and air-based interceptors would likely be safe. Adapted from [Wells 2024, Fig. 2].

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 2021; Rahmat 2021].

As noted previously, the kinematically allowed basing areas shown Figure 5(a) assume the interceptor is fired with zero decision time, to show what the capability of the missile defense system would be if a concept of operations that prescribes this firing protocol were adopted. Providing 30 seconds of decision time would reduce the radii of the kinematically allowed basing areas for a 5 km/s interceptor fired against a Hwasong-15 by about 120 km, significantly reducing the possible basing areas [Wells 2024].

Figure 5(a) shows that if the intercept could be timed to occur at about 260 seconds after our model of the Hwasong-15 was launched toward Boston, which would require precise knowledge of its performance and intended target, and if the off-shore reach of North Korea's defenses is 100 km, then there would be a strip of the East Sea/Sea of Japan off the eastern coast of North Korea that would be a possible basing area from which a 5 km/s interceptor could be fired with no decision time and intercept the Hwasong-15 at 260 seconds. If instead the off-shore reach of North Korea's defenses is 200 km, there would be only a very small possible basing position off the eastern coast of North Korea.

For intercepts significantly earlier than 260 seconds after a Hwasong-15 has been launched from a launch site in north or north- central North Korea in the direction of the northeastern United States, the kinematically allowed basing areas that would allow our model interceptors to intercept it would be significantly smaller, because the interceptor flight time would be less [Wells 2024]. For intercepts significantly later than 260 seconds after a Hwasong-15 has been launched, the kinematically allowed basing areas would have larger radii than those for intercepts at 260 seconds but would be centered further inland. Hence a later intercept would benefit the defense little: the interceptor is chasing the accelerating Hwasong-15 ICBM from behind while the ICBM is moving rapidly inland, away from possible interceptor basing locations [Wells 2024].

In summary, with our assumptions there would be a strip in the sea off the eastern coast of North Korea where 5 km/s interceptors might be safe from North Korean sea and air defenses and be able to reach a Hwasong-15 early enough to prevent its warhead from striking a city in the northeastern United States, but a 4 km/s interceptor would not be able to reach the Hwasong-15 early enough from possible basing locations.

Consider now a Hwasong-15 ICBM launched in the direction of Los Angeles from a launch site in northern North Korea. Our model of the Hwasong-15 shows that if it were launched in this direction, its warhead(s) could strike targets in the Aleutian Islands unless it is intercepted earlier than 260 seconds after launch but they could be prevented from striking Los Angeles if the Hwasong-15 is intercepted earlier than 285 seconds after it was launched.

Figure 5(a) shows that if the defense planned to intercept a Hwasong-15 headed in the direction of Los Angeles about 260 seconds after launch, there would be areas on or over the East Sea/Sea of Japan where either 4 km/s or 5 km/s interceptors could probably be safely based and yet prevent the Hwasong-15's warheads from striking Los Angeles. If instead the defense planned to intercept the Hwasong-15 headed in the direction of Los Angeles later than 260 seconds after launch, planning to defend only the lower 48 states, it could either make use of a larger possible basing area on or over the East Sea/Sea of Japan, or allow some decision time before firing its interceptors. Depending on how long the defense decided to wait to fire its interceptors, there would be some possible basing area from which 5 km/s interceptors could intercept Hwasong-15s launched from northern North Korea early enough to prevent their warheads from striking the Midwest or the U.S. West Coast [Wells 2024].

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 launched from north-central North Korea toward targets in the U.S. Northeast early enough to defend them, interceptors would have to have burnout velocities of about 5 km/s or more to be safe from North Korea's sea and air defenses, even if the interceptors were fired with zero decision time. Third, there are locations where interceptors like these could be safely based and reach Hwasong-15s launched in the direction of targets in the Midwest or on the U.S. West Coast early enough to prevent their warheads from striking 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.

Defending against the Hwasong-18.

The model of North Korea's solid-propellant Hwasong-18 ICBM used here (see [Wells 2024]) could be prevented from launching a warhead that could strike Boston if it were intercepted no later than 145 seconds after it was launched. Intercepting it earlier would protect Alaska as well as the U.S. East and West Coasts. It would also eliminate the possibility of a dog-leg maneuver to better evade a boost-phase defense and instead strike a city in Alaska.

However, as Figure 5(b) shows, there is no possible basing area from which even a 5 km/s interceptor fired with zero decision time could reach the model of the Hwasong-18 ICBM used here at or before 145 seconds after it was launched, if the ICBM were launched from a site in northwest or north-central North Korea. Such a boost-phase defense therefore could not prevent warhead(s) launched by our model of the Hwasong-18 from striking cities in the northeastern Unites States, such as Boston.

Figure 5(b) shows further that there would be no possible basing area from which even a 5 km/s interceptor fired with zero decision time could reach our model of the Hwasong-18 ICBM early enough to prevent its warhead(s) from striking cities on the U.S. West Coast such as Los Angeles, if the ICBM were launched from a site in northwest or north-central North Korea and North Korea's sea and air defenses can reach 200 km off its eastern coast. If instead North Korea's sea and air defenses can reach only 100 km off its eastern coast, there would be a very small possible basing area from which 5 km/s interceptors could reach our model of the Hwasong-18 ICBM early enough to prevent its warhead(s) from striking cities on the U.S. West Coast. Providing 30 seconds of decision time would reduce the radii of the kinematically allowed basing areas by about 135 km for a 5 km/s interceptor fired against our model of the Hwasong-18, eliminating any possible basing area, even if the range of North Korea's sea and air defenses were only 100 km.

The launch site assumed in Figures 5(a) and 5(b) is one of the more challenging launch sites for a boost-phase defense against ICBMs because of its distance from the East Sea/Sea of Japan. Also, North Korea may consider it safer from attack by an adversary than other possible launch sites because it is so close to North Korea's border with China. ICBMs launched from some other sites in North Korea would be easier to intercept, but North Korea may not choose to launch its ICBMs from sites it considers more vulnerable to attack or that would make its ICBMs easier to intercept.

Interceptor and kill vehicle requirements. Unless the rocket motor of the interceptor's kill vehicle can begin operating either continuously or in pulsed mode soon after the kill vehicle has been released from the interceptor's boost stages, having an interceptor with a boost phase that is short lengthens its coasting phase, which is the phase when its booster stack has burned out but the rocket motor of its kill vehicle has not yet begun operating. A lengthy coast phase is undesirable, because during this phase the interceptor cannot adjust its trajectory to compensate for unexpected (deliberate or incidental) accelerations of the target ICBM. Hence a lengthy coasting phase reduces the likelihood that the interceptor's kill vehicle will be able to hit the target ICBM [see APS 2003, Secs. 2.2, 12, and 14, and Appendices B and C]. For this reason, we used the interceptor models of [Wells 2024], which have total burn times of 50 seconds—the total burn time of the 5 km/s interceptor used in the 2003 APS Report [APS 2003, Table 5.3]—to construct the kinematically allowed basing areas shown in Figure 5.

Some other authors (see, e.g., [Garwin 2018a; Garwin 2018b]) have chosen to use fast-burning 4 km/s and 5 km/s interceptor models, with boosters that burn out after only 25 seconds. The shorter burn time increases the time the interceptor is traveling at a higher speed, but it only minimally increases the range of the interceptor. The more rapid acceleration of these interceptors would increase their reach slightly if they were traveling in a vacuum, but in practice it does not, because they have a higher velocity lower in the atmosphere, which increases atmospheric drag and reduces the increase in the interceptor's reach. For example, reducing the 5 km/s interceptor's total burn time from 50 seconds to 25 seconds would increase its reach by only about 15 km for a Hwasong-15 lofting its warhead toward Boston but would lengthen its coasting phase, reducing the likelihood that its kill vehicle would be able to hit the target ICBM.

The kill vehicles carried by boost-phase interceptors must reach the ICBM early enough to prevent the ICBM from giving its warhead(s) the velocity needed to strike the intended target and must have the sensors and cumulative divert velocity required to home in on and hit the dim missile body in the presence of its bright exhaust plume while the missile is moving at a velocity of about 6 km/s and accelerating and possibly maneuvering somewhat unpredictably [NRC 2012, 2-31].

Hitting the missile's hardbody normally requires a kill vehicle that can begin maneuvering soon after it separates from its booster stack, has a sensor—such as a light or infrared detection-and-ranging (LIDAR) system—and has a cumulative divert velocity of at least 2.5 km/s [APS 2003, Sec. 12.3.2]. The defensive 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 battle management task of simultaneously assigning multiple interceptors to multiple attacking ICBMs and guiding multiple kill vehicles to their targets.

Countermeasures to boost-phase intercept. 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, 69]. In order to avoid arguments about what countermeasures to boost-phase intercept are or are not feasible, the 2003 APS report considered only countermeasures that have actually been deployed in operational systems during the past 60 years and that North Korea is likely to be able to implement.

Examples include (a) launching several ICBMs nearly simultaneously (a salvo or staggered launch); (b) launching decoy rockets simultaneously with the ICBM, to confuse the defense; (c) deploying the ICBM's warhead (re-entry vehicle) while the ICBM's final stage is still burning; (d) deploying rocket-propelled decoys and jammers during the flight of the ICBM's upper stages; and (e) programming the upper stages to fly evasive maneuvers, possibly in conjunction with deployment of decoys and jammers. Each of these possible countermeasures could pose a significant challenge to a boost-phase defense system.

Other challenges of boost-phase intercept. 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. Depending on where on the ICBM the collision occurs, it 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. If the intercept does not cause the warhead to explode, it may remain functional and detonate when or before it hits the ground at some point short of its intended target. For ICBMs launched from North Korea toward the United States, the resulting nuclear detonation would not occur in North Korea but instead in China, Russia, Canada, or locations within the United States that are closer to the launch site 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 that may not be possible to solve. The seriousness of this problem is mitigated by its context: such a shortfall would occur during a nuclear war and the warhead would likely explode in or over an area with a relatively low population density. Addressing this problem would require considering the design and performance requirements of a system that would be able to disable the warhead of an adversary's ICBMs with certainty before the warhead separates from the ICBM. This is a demanding task (for a detailed discussion of this problem, see [APS 2003, Secs. 5.8 and 13.2]).

We do not attempt to address this problem in the present report. Instead, this report focuses on outlining some of the necessary system elements and performance requirements for a system that would be able to prevent an ICBM's warhead from striking intended targets in various parts of the continental United States by terminating the ICBM's thrust sufficiently early.

While such a boost-phase defense system could potentially reduce the number of warheads that a midcourse defense system would face, it could also make midcourse defense more challenging. For example, if a boost-phase intercept destroys the booster but not the warhead above the atmosphere, the intact warhead may be accompanied by debris from the destroyed booster. This debris could confuse the midcourse defense system's sensors. The boost-phase intercept could also cause the ICBM's warhead to begin tumbling or spinning in ways the midcourse defense has not anticipated, making it difficult for the midcourse system's kill vehicles to identify, home on, and strike the warhead (see [APS 2003, Sec. 13.3]).

BOOST-PHASE INTERCEPT SYSTEMS

Land and sea-based rocket interceptors.
As discussed in the previous subsection, 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 a target in the United States.

Sea-based rocket interceptors could in principle intercept ICBMs launched from North Korea in time to prevent their warheads from striking targets in the continental United States if the interceptors were fast enough. However, interceptors that could fit in Aegis vertical launch system (VLS) tubes have limited velocities. The fastest notional boost-phase interceptor that the 2012 National Academies study assumed could fit in a VLS tube had a fly-out velocity of only about 4.5 km/s [NRC 2012, 44]. This is the reported fly-out velocity of the SM-3 Block IIA interceptors [CSIS 2023].

As Figure 5 shows, if a liquid-propellant ICBM like the Hwasong-15 model we use were launched from northwest or north-central North Korea, 4.5 km/s interceptors, the fastest that could be carried by Aegis ships, could reach it in time to prevent its warhead from striking targets on the U.S. East Coast only if the ships were positioned in a narrow band of the East Sea/Sea of Japan off the eastern coast of North Korea or Russia and the interceptors were fired with zero decision time.

Depending on its maximum range, an ICBM like the Hwasong-15 might be able to evade intercept by such a system by starting on a trajectory toward the U.S. East Coast and then shifting its trajectory to strike targets in Alaska or the U.S. Northwest. Interceptors fired from VLS tubes on Aegis ships positioned in possible basing locations could reach long-burning liquid-propellant ICBMs in time to prevent their warheads from striking targets on the U.S. West Coast.

In order for Aegis ships to attempt intercept of a salvo of 10 ICBMs like the Hwasong-15, their VLS tubes would have to be preloaded with 10 to 20 interceptors, depending on the expected effectiveness of the interceptors in intercepting the ICBMs and the countermeasures the missile defense system expects to encounter. Interceptors carried in the VLS tubes of Aegis ships on-station in possible basing locations from which they could intercept liquid-propellant ICBMs like the Hwasong-15 early enough to prevent their warheads from striking targets in the continental United States could not reach solid-propellant ICBMs like the Hwasong-18 early enough to prevent their warheads from striking targets in the Midwest or on the East Coast.

Aegis ships are being considered for use as platforms for rocket interceptors that would be used to intercept ICBM warheads late in their midcourse flight, but this concept has been criticized as an inefficient use of these expensive, very capable ships [CRS 2024b, 19–21]. The same criticism could be made of a boost-phase missile defense system that requires keeping Aegis ships continuously on-station off the eastern coasts of North Korea and Russia. This criticism would be less relevant if the plan were to surge ships to positions off these coasts when tensions are high or there is a crisis [MDR 2019, XV and 56].

Drone-based rocket interceptors.
A system of drone-based rocket interceptors for a boost-phase defense against ICBMs launched from North Korea could be designed not to threaten current Russian or Chinese ICBMs [Garwin 2017; Goodby 2018]. Such a system would require high-altitude, long-duration drones able to carry high-speed rocket interceptors capable of intercepting a maneuvering ICBM (see [Wilkening 2004; Garwin 2017; Garwin 2018a; Garwin 2018b; Goodby 2018; Postol 2018; Wells 2024]). These drones would need to be able to loiter on-station for ten or twenty hours, or perhaps even longer, and as explained above, might have to stay 100 to 200 km away from the eastern coast of North Korea to be safe from North Korean air defenses.

If the off-shore reach of North Korean air defenses is 200 km, then with our assumptions there would be only a very small safe basing area over the East Sea/Sea of Japan from which drone-based 5 km/s interceptors could reach our model of the Hwasong-15 if it were launched from north-central North Korea early enough to prevent its warhead from striking targets in the northeastern United States, even if the interceptors were fired with no decision time.

If instead North Korean air defenses can reach only 100 km off-shore, there would be a strip of the East Sea/Sea of Japan off the eastern coast of North Korea where drone-based 5 km/s interceptors could be safely positioned and be able to reach our model of the Hwasong-15 if the interceptors were fired with no decision time. With these assumptions, a system like this could defend the entire continental United States, because the northeastern United States is the most difficult region for such a system to defend.

Drone-based 4 km/s interceptors could reach our model of the Hwasong-15 launched from north-west or north-central North Korea toward the U.S. Midwest or West Coast in time to prevent its warhead(s) from striking targets in these parts of the United States but they would not be fast enough to defend the northeastern part of the United States. Such interceptors could reach Hwasong-15s launched from other sites in North Korea that would make them vulnerable to such a defensive system.

Even 5 km/s drone-based interceptors would not be fast enough to prevent a solid-propellant ICBM like the Hwasong-18 from striking targets anywhere in the United States from a variety of possible launch sites in North Korea (see Figure 5(b) above, Figure 5.9 of [APS 2003], and Figure 2 of [Wells 2024]).

Some have advocated deploying drone-based rocket interceptors using already available, off-the-shelf parts in order to deploy them quickly and cheaply (see, e.g., [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 they would take to reach the target ICBM, decreasing the probability they would be able to intercept the ICBM successfully (see [APS 2003], Secs. 2.2, 12, and 14, and Appendices B and C).

If a decision were made to develop a boost-phase defense system that would use drone-based rocket interceptors to defend the United States against liquid-propellant ICBMs like the Hwasong-15, 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 high-altitude flight times longer than those of current drones and capable of carrying heavier interceptors.

Interceptors, kill vehicles, and drones optimized for such a system 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 liquid-propellant ICBM or a salvo of 10 of them have not been studied.

The broader 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.

Aircraft-based rocket interceptors.
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, in order for the missile to be able to reach the ICBM before it reaches altitudes greater than 30 km, where interceptors like these 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.

Space-based rocket interceptors.
The limitations on the performance of boost-phase intercept systems that use surface-based interceptors imposed 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 interceptor 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 subsection 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 primary liquid-propellant ICBM, its Hwasong-15, has a full burn time of 289 seconds, significantly longer than the 240-second burn time of the liquid-propellant model ICBM considered by the APS and National Academies studies. As noted previously, the longer burn time of the Hwasong-15 somewhat reduces the reach-versus-time challenge, 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, North Korea has now tested and deployed a solid-propellant ICBM, the Hwasong-18, which is thought to have a total burn time of only about 170 seconds, much shorter than the 289-second total burn time of the Hwasong-15. Intercepting the Hwasong-18 during its boost phase would therefore be far more challenging than intercepting the Hwasong-15.

In addition, 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 interceptor will 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 they would need to anticipate the possible types and likely performances of North Korea's ICBMs a decade or more in the future, because it would take a decade or more to design and construct a system of space-based rocket interceptors able to defend the United States against the threat we have just described, 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 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 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 (see Figure 6) would need to be deployed to ensure that at least one would be in position to intercept each of a "salvo" of four liquid-propellant ICBMs like the Hwasong-15 launched within three minutes or so. About 4,000 space-based interceptors would be needed to attempt to counter a salvo of ten liquid-propellant ICBMs like the Hwasong-15. If instead the system was 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 such ICBMs and about 5,500 would be needed to attempt to counter a salvo of ten of them.

Making the same assumptions as before and again using the methodology of the 2003 APS study [APS 2003, Ch.6], we estimate that a constellation of about 16,000 interceptors would be needed to attempt to counter a rapid salvo of ten solid-propellant ICBMs like the Hwasong-18. In order to allow 30 seconds of decision time, about 36,000 interceptors would be required.

The orbital motion of the interceptors would, on a timescale of about 200 seconds, repopulate the coverage that constellations like these would provide. Therefore, if the defense could be certain that all ICBM launches would be spaced apart by at least 200 seconds, it could treat multiple launches as a sequence of single launches.

A system designed to be able to defend against the launch of a single Hwasong-15 without any decision time would need a constellation of at least 400 interceptors. At least 500 interceptors would be needed if the system were to prescribe 30 seconds of decision time. For comparison, a system designed to be able to defend against the launch of a single Hwasong-18 without any decision time would need a constellation of at least 1600 interceptors. A constellation of at least 3600 interceptors would be needed if the system were to designed to allow 30 seconds of decision time.

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 have chosen a final "fly-out" velocity of 4 km/s because the 2003 APS study found that for its baseline system, a two-stage interceptor with a fly-out 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 require 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 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

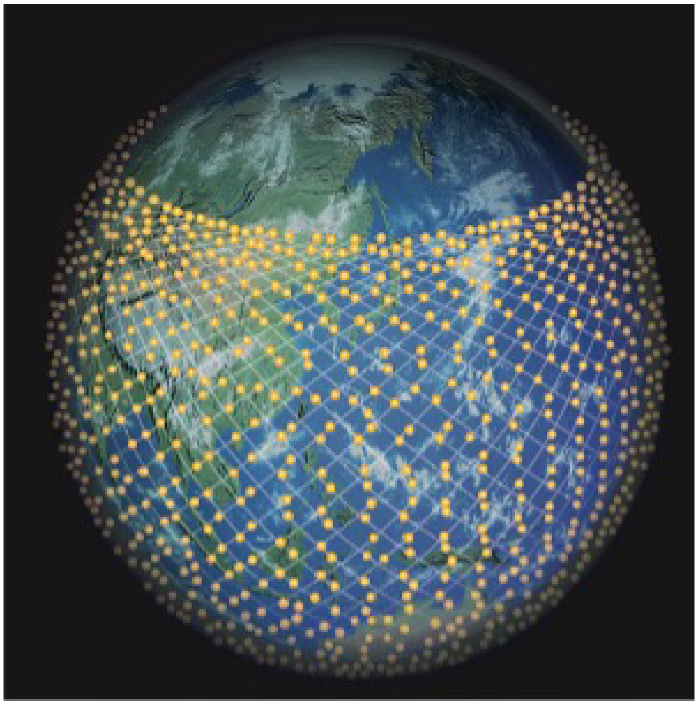

Figure 6 View of Earth showing the constellation of 1,600 space-based interceptors that would berequired to ensure that one is available to intercept a rapid salvo launch of four Hwasong-15 ICBMs from North Korea, if the system was designed to fire interceptors almost automatically, i.e., if no time 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. Adapted from [NRC 2012, Fig. 2-20].

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 of the solid-propellant Hwasong-18 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 the reduction that is possible 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. Creating a 400-interceptor constellation that could in principle defend against a single Hwasong-15 liquid-propellant ICBM 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 providing any time to decide whether to fire interceptors, or $100 billion to $180 billion for a system of 5,500 interceptors 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.

Creating a constellation of interceptors that could in principle defend against a single Hwasong-18 solid-propellant ICBM would require placing about 1,000 tonnes in low Earth orbit and would cost about four times as much as a constellation that could in principle defend against a single Hwasong-15.

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 plans to launch 12,000 satellites totaling 3,000 tonnes into orbit for a total 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.

Laser weapons.
Practical laser weapons for boost-phase intercept would require laser systems compact and light enough to be carried on an aircraft, drone, or ship, 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 Megawatt 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, 54–58]. 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 laser weapons to disable threatening targets are advancing slowly [CRS 2024b; CRS 2024c; GAO 2023]. While the Missile Defense Agency has backed away from developing defensive laser weapons, various branches of the U.S. military have continued to pursue this technology for less demanding purposes [Judson 2021b]. In 2024 the Army sent 10- to 50-kilowatt laser weapons intended for short-range air defense to the Middle East to test them in an operational setting [Keller 2024a; Keller 2024b]. The results demonstrated some of the severe challenges such weapons face when attempts are made to use them in a real-world environment [Roque 2024]. The Army is also seeking to develop 100- to 300-kilowatt laser systems for possible eventual use against mortars, rockets, drones, and aircraft [Eversden 2022; Roque 2023]. The Navy is currently deploying the 60-kilowatt 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].

These efforts illustrate some of the many technical challenges to building and deploying laser weapons capable of disabling even targets that are much less challenging to disable than an ICBM. These challenges include achieving enough laser power to disable the target, especially fast-moving targets like missiles. At current power levels, even to disable a drone a laser must track it and remain focused on it for some seconds [Tucker 2024]. The demand for electrical power made by laser weapons is also daunting—many of the Navy's most modern destroyers do not have enough electrical power available to power a 60-kilowatt laser [Keller 2023].

Other challenges include propagating the laser beam through the atmosphere while maintaining sufficient focus to be able to disable the target. Many substances in the atmosphere, such as water vapor, sand, dust, salt particles, and other air pollutants, and atmospheric turbulence can defocus the laser beam [CRS 2024b, 32]. This is a challenge for all laser weapons, but particularly for those in vehicles or platforms on the ground or on ships at sea. Another challenge is cost. According to a recent Congressional Research Service report, "the per-unit cost of a 60 kilowatt class laser with relatively mature beam control and combat system integration at moderate production rates will be approximately $100 million in limited quantities. For weapons at greater power and/or beam control complexity, the estimates range up to $200 million per unit for lasers in the 250 kilowatt class" [CRS 2023a, 30].

There is widespread agreement that laser weapons that could disable 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 [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 Section 2: North Korea's ICBM Capabilities), 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 Section 3: Challenges of Missile Defense, and the more detailed discussions in Section 4: Midcourse Intercept Systems and Section 5: Boost-Phase Intercept Systems).

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 warhead-intercept systems and boost-phase missile 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 warhead-intercept system, the Aegis BMD system when used for midcourse warhead-intercept, and the ship- and drone-based rocket-interceptor systems that have been proposed for boost-phase missile intercept. We explained the current and near-term abilities of these systems to defend against 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 warhead-intercept to the severe reach vs. time problem of boost-phase missile 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

Frederick K. Lamb (Study Group Chair) is Research Professor of Physics and of Astronomy, Brand and Monica Fortner Chair of Theoretical Astrophysics emeritus, and a core faculty member in the Program in Arms Control & Domestic and International Security at the University of Illinois. A member of the American Academy of Arts and Sciences and a Fellow of the American Physical Society (APS), his scientific research has focused on high-energy and relativistic astrophysics. He has been a consultant to the Defense Department, national laboratories, Congressional committees, and the Institute for Defense Analyses on defense and security matters, including space policy, ballistic missiles and missile defenses, and technical aspects of nuclear test bans. He co-chaired the 2003 APS study of boost-phase missile defense and shared the American Physical Society's 2005 Leo Szilard Lectureship Award.

Laura Grego (Study Group Co-chair) is the research director of the Global Security Program at the Union of Concerned Scientists (UCS). Before joining UCS, Dr. Grego was a postdoctoral researcher at the Harvard-Smithsonian Center for Astrophysics. She works at the intersection of science and policy on the topics of nuclear weapons, missile defense, and space security. She is an associate editor of the journal Science and Global Security, a fellow of the American Physical Society, and was a member of its Panel on Public Affairs from 2019-2024. She received the American Physical Society's 2023 Leo Szilard Lectureship Award.

James D. Wells (Study Group Co-chair) is a Professor of Physics at the University of Michigan. A Fellow of the American Association for the Advancement of Science and the American Physical Society, his research interests include theoretical high-energy physics and the intersections of science and national security policy. A former chair of the American Physical Society's Panel on Public Affairs (POPA), he co-led the 2018 POPA study "Neutrons for the Nation: Discovery and Applications while Minimizing the Risk of Nuclear Proliferation".

William Priedhorsky is former Director of the Laboratory-Directed (internal) R&D Program at Los Alamos National Laboratory. A Los Alamos and American Physical Society (APS) Fellow, he has a broad range of expertise, including on space hardware and space-based sensors. He was previously program manager for proliferation detection, later served as chief scientist of Los Alamos' Threat Reduction directorate, was a member of the 2003 APS study of boost-phase missile defense, and shared the American Physical Society's 2005 Leo Szilard Lectureship Award.

David K. Barton was an independent consultant. A member of the National Academy of Engineering, he was also a Fellow of the Institute of Electrical and Electronics Engineers (IEEE). As an expert on the use of radars for missile launch detection, sensor cuing, missile tracking, and target discrimination, he served as a member of the NRC's Air Force Studies Board, as chair of the Committee on the E-3A Radar, and as chair of the Committee on Advanced Airborne Surveillance Radar. He was a member of the 2003 American Physical Society and the 2012 National Academy of Sciences panels on missile defense.

Philip E. Coyle was a Senior Science Fellow at the Center for Arms Control and Non-Proliferation. A renowned expert on nuclear weapons, missile defense, national security, and defense spending, his recent work focused heavily on analyses of ground-based midcourse defense. He spent more than three decades working on nuclear weapons and related programs at Lawrence Livermore National Laboratory, becoming Deputy Laboratory Director, before serving as Assistant Secretary of Defense and Director, Operational Test & Evaluation and subsequently as Associate Director for National Security and International Affairs in the White House Office of Science and Technology Policy.

Steve Fetter is a professor in the School of Public Policy at the University of Maryland. He is a Fellow of the American Physical Society, a former member of the APS Panel on Public Affairs, and a recipient of the APS Leo Szilard Lectureship and Joseph A. Burton Forum awards. He has served in the departments of State and Defense and led the national security and international affairs division in the White House Office of Science and Technology Policy. He is a member of the National Academy of Sciences' Committee on International Security and Arms Control and has contributed to 10 reports by the National Academies.

Alec Gallimore is the Provost and Chief Academic Officer of Duke University and the Alfred J. Hooks E '68 Distinguished Professor. Prior to his appointment at Duke in 2023, he held multiple leadership roles over his 30+ year career at the University of Michigan, including as Robert J. Vlasic Dean of Engineering, associate dean for academic affairs, associate dean for research and graduate education, and associate dean at the Horace H. Rackham School of Graduate Studies. Dr. Gallimore is a leader in the field of advanced spacecraft propulsion and founded a laboratory that is developing the plasma drive system that may ultimately propel humans to Mars. His work has been recognized with the AIAA's Wyld Propulsion Award, the Electric Rocket Propulsion Society's Ernst Stuhlinger Medal, and induction into the National Academy of Engineering.

Cynthia K. Nitta is the Future Deterrent Program Director in the Weapon Physics and Design Program of the Lawrence Livermore National Laboratory (LLNL) Strategic Deterrence Directorate. She is responsible for the design physics elements to assess emerging threats to the nuclear stockpile, technology development and certification of future concepts to mitigate those threats, and LLNL activities directly supporting system technology maturation funded by the National Nuclear Security Agency (NNSA). Dr. Nitta has extensive experience in nuclear science and technology, and a strong interest in supporting national security and policy; she recently served on a national Failsafe Study of stockpile safety and surety, and currently serves on the Visiting Committee of the M.I.T. Nuclear Engineering and Science Department. She has served on the boards of directors for national organizations that promote STEM education for girls and civil rights.

Aric Tate is a physicist and nuclear engineer who received his doctorate at the University of Illinois during the course of this study. His research has included developing instruments to detect and track nuclear explosive material and the development of highly radiation resistant detectors for use at particle accelerators. He has also studied proton-ion collisions at the Large Hadron Collider (LHC) at CERN to better understand the role of proton size fluctuations in the interpretation of nuclear collision data. Throughout his graduate career, he assisted with teaching and development of the University of Illinois physics course "Nuclear Weapons and Arms Control". He is currently a postdoctoral researcher in nuclear physics at Illinois, carrying out jet analyses with the ATLAS detector at the LHC.

FIGURES

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