



U.S. Hypersonic Weapons and Alternatives



At a Glance

The Army, Navy, and Air Force are each developing hypersonic missiles—nonnuclear offensive weapons that fly faster than five times the speed of sound and spend most of their flight in the Earth’s atmosphere. Those missiles are intended to be maneuverable and capable of striking targets quickly (in roughly 15 minutes to 30 minutes) from thousands of kilometers away.

In this report, the Congressional Budget Office analyzes the hypersonic weapons being developed by the U.S. military and compares them with less expensive existing or potential weapons that might fill similar roles, such as ballistic missiles or cruise missiles. CBO reached the following conclusions:

- **Technological challenges must still be overcome to field hypersonic missiles.** The fundamental remaining challenge involves managing the extreme heat that hypersonic missiles are exposed to by traveling at high speeds in the atmosphere for most of their flight (unlike cruise missiles, which fly in the atmosphere at lower speeds, or ballistic missiles, which mainly fly above the atmosphere). Shielding hypersonic missiles’ sensitive electronics, understanding how various materials perform, and predicting aerodynamics at sustained temperatures as high as 3,000° Fahrenheit require extensive flight testing. Tests are ongoing, but failures in recent years have delayed progress.
- **Both hypersonic and ballistic missiles are well-suited to operate outside potential adversaries’ antiaccess and area-denial (A2/AD), or “keep-out,” zones.** The Department of Defense has developed a strategy to use accurate, long-range, high-speed missiles early in a conflict to neutralize the A2/AD zones being developed by potential adversaries, such as China and Russia. Both hypersonic missiles and ballistic missiles equipped with maneuverable warheads could provide the combination of speed, accuracy, range, and survivability (the ability to reach a target without being intercepted) that would be useful in the military scenarios CBO considered. However, many missions do not require such rapid strikes. For those missions, less costly alternatives to both hypersonic and ballistic missiles exist, including subsonic cruise missiles. Hypersonic weapons would mainly be useful to address threats that were both well-defended and extremely time-sensitive.
- **Hypersonic missiles would probably not be more survivable than ballistic missiles with maneuverable warheads in a conflict, unless the ballistic missiles encountered highly effective long-range defenses.** Hypersonic missiles can neutralize long-range (midcourse) defenses because they fly inside the atmosphere, below the altitude where midcourse ballistic missile defenses typically operate. Hypersonic weapons can also maneuver unpredictably at high speeds to counter short-range defenses near a target, making it harder to track and intercept them. Ballistic missiles are also difficult to defend against, particularly if they are equipped with countermeasures to confuse midcourse missile defenses and maneuverable warheads to defeat short-range missile defenses. Only very effective long-range defenses would be likely to threaten ballistic missiles in midcourse; to date, no potential U.S. adversaries have deployed such defenses.
- **Hypersonic missiles could cost one-third more to procure and field than ballistic missiles of the same range with maneuverable warheads.** CBO estimates that buying 300 ground- or sea-launched, intermediate-range ballistic missiles with maneuverable warheads and sustaining the missile system for 20 years would cost a total of \$13.4 billion (in 2023 dollars). The same number of comparable hypersonic missiles would cost about one-third more, \$17.9 billion, CBO estimates. (Neither estimate includes the cost overruns that are often associated with technically challenging programs.) The higher costs for hypersonic missiles partly reflect the complexity of building systems that can withstand the heat of hypersonic flight.

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Notes

Unless this report indicates otherwise, all years referred to are federal fiscal years, which run from October 1 to September 30 and are designated by the calendar year in which they end.

Numbers in the text, tables, and figures may not add up to totals because of rounding.

On the cover:

Left: Artist's rendering of the Air Force's Air-Launched Rapid Response Weapon with the Tactical Boost Glide vehicle at its tip. Lockheed Martin illustration.

Top right: Test launch by the Army and the Navy of the Common Hypersonic Glide Body in March 2020. U.S. Navy photo.

Bottom right: Artist's rendering of the Defense Advanced Research Projects Agency's (DARPA's) Hypersonic Air-Breathing Weapon Concept cruise missile. DARPA illustration.

Summary

After many decades of conducting basic research, the Department of Defense (DoD) recently increased its spending to develop technology for hypersonic weapons. The Air Force, Army, and Navy all plan to field hypersonic missiles within the next few years. China and Russia have stated that they are also fielding such weapons.

The term “hypersonic weapon” is often misapplied. Strictly speaking, it refers to a missile that travels at speeds at least five times the speed of sound in air (Mach 5 or above) and that spends most of its flight inside the Earth’s atmosphere (rather than in space), where it can use aerodynamic design features to maneuver.

The combination of long range, high speed, and maneuverability distinguishes the hypersonic weapons that DoD is developing from the conventional strike weapons in the U.S. military’s current inventory. Hypersonic missiles are considered a possible counter to the antiaccess and area-denial (A2/AD) systems that potential near-peer adversaries such as China and Russia are deploying to prevent U.S. forces from operating freely in their regions. In theory, hypersonic weapons could be launched from outside the range of those systems and could reach targets within minutes over medium to intermediate ranges (from hundreds to a few thousands of kilometers), with a high degree of accuracy and less vulnerability to defenses than existing missiles.¹

The Congressional Budget Office analyzed the relative capabilities and possible costs of hypersonic missiles and potential alternatives in scenarios in which long-range, rapid-response weapons might be useful. CBO found that hypersonic missiles with sufficient ranges for A2/AD scenarios—at least 1,000 kilometers (km), or about 600 miles, for missiles launched from aircraft and at least 3,000 km, or about 1,900 miles, for missiles launched from the ground or sea—have the speed to be useful in the early stages of a conflict with a near-peer adversary.

1. CBO used kilometers in this analysis because they are the preferred unit for measuring distance in many military and engineering contexts. One kilometer equals 0.62 miles.

Hypersonic missiles with those ranges, however, would be more expensive than similar ballistic missiles and pose much greater technical challenges (see Figure S-1). CBO estimates that hypersonic missiles would cost roughly one-third more than ballistic missiles with maneuverable warheads that had the same range and accuracy and traveled at similar speeds. (The United States does not currently field such ballistic missiles, but the technology for them is well developed.)

Hypersonic weapons could be better than ballistic missiles at penetrating long-range missile defenses that operate outside the atmosphere. So far, however, no potential U.S. adversaries have succeeded in developing such defenses. Against shorter-range defenses, it is unclear whether hypersonic missiles would have an advantage over ballistic missiles with maneuverable warheads.

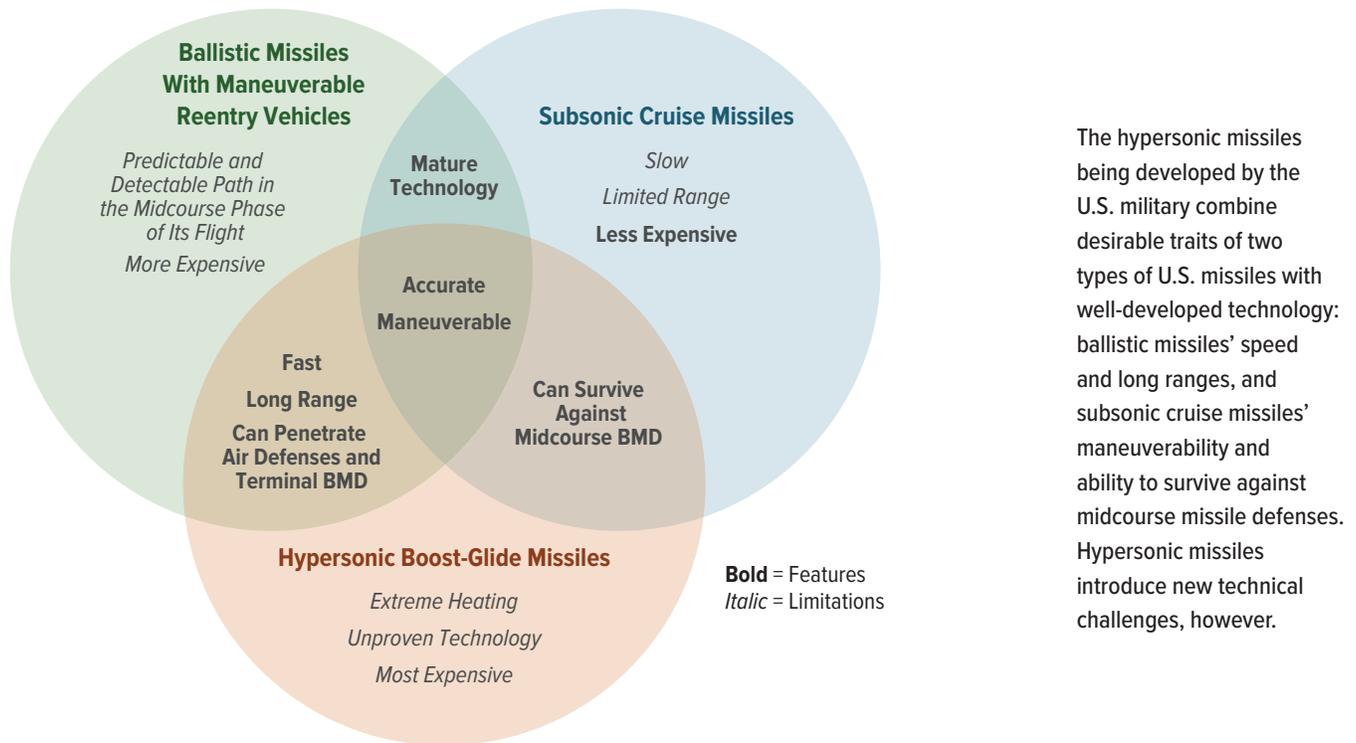
Given their cost, hypersonic weapons would provide a niche capability, mainly useful to address threats that were both well-defended and extremely time-sensitive (requiring a strike in 15 minutes to 30 minutes). If time was not a concern, much cheaper cruise missiles could be used. If targets were time-sensitive but were not protected by defenses that effectively intercept incoming ballistic missiles in the middle of their flight, less costly ballistic missiles with maneuverable warheads could be used.

How Did CBO Compare Planned Hypersonic Weapons and Possible Alternatives?

To evaluate hypersonic missiles and potential alternatives, CBO considered possible scenarios for their use and what those scenarios would require in terms of missiles’ range, time to reach their targets (responsiveness), and ability to reach those targets without being intercepted (survivability). Both China and Russia have long-range A2/AD systems that are tailored to prevent the United States from achieving air, land, and sea superiority in their areas during a conflict. A long-distance, highly responsive weapon could be useful in other circumstances, such as when fleeting intelligence was available about the location of a high-value target (a missile launcher or the head of a terrorist organization, for example). CBO concluded that

Figure S-1.

Comparison of the Features and Limitations of Hypersonic Missiles and Alternatives



The hypersonic missiles being developed by the U.S. military combine desirable traits of two types of U.S. missiles with well-developed technology: ballistic missiles’ speed and long ranges, and subsonic cruise missiles’ maneuverability and ability to survive against midcourse missile defenses. Hypersonic missiles introduce new technical challenges, however.

Data source: Congressional Budget Office.

BMD = ballistic missile defense.

in A2/AD scenarios centered on the South China Sea and the Baltic region, there would probably be a number of time-sensitive, high-value targets for which rapid strikes from longer distances could be useful. In evaluating those scenarios, CBO also considered whether potential adversaries had missile defense systems to defend against an incoming U.S. missile.

CBO identified potential weapons that could be employed in such scenarios and estimated their performance using metrics describing range, responsiveness, and survivability. The weapon systems that CBO considered include existing systems, such as subsonic cruise missiles like the Navy’s Tomahawk Land Attack System, and possible future systems, such as hypersonic cruise missiles and hypersonic boost-glide missiles like those being developed by DoD. (A cruise missile is powered by an engine throughout its flight; a boost-glide missile is initially accelerated to a high altitude using a rocket and then glides at high speed through the atmosphere to its target.) CBO also considered hypothetical ballistic missiles with maneuverable warheads that would provide accuracies similar to those predicted for hypersonic boost-glide missiles.

CBO then narrowed its list of weapon systems to only those technologies that could meet the more demanding requirements for range, responsiveness, and survivability in the relevant scenarios. CBO analyzed the characteristics of each of those systems and estimated the cost to produce them.

What Did CBO Find?

To operate effectively in an adversary’s A2/AD zone, the U.S. military might need to strike a small number of targets in as little as an hour at ranges that could be as long as 3,000 km to 5,000 km (about 1,900 miles to 3,400 miles), CBO estimates. Such targets include coastal air-defense systems, long-range strike systems, and over-the-horizon radars that are essential to maintaining an A2/AD zone. By degrading an adversary’s long-range strike systems and defenses, the United States could limit the effects of A2/AD systems early in a conflict, allowing it to use a broader arsenal of shorter-range and less survivable weapons thereafter.

Of the potential alternatives that CBO examined for those types of missions, only ballistic missiles equipped with



maneuverable reentry vehicles (MaRVs) and hypersonic boost-glide missiles would have the combination of speed and range to strike targets under the strict time constraints associated with the most challenging A2/AD scenarios.

Comparison of Hypersonic Boost-Glide Missiles and Ballistic Missiles

CBO concluded that hypersonic missiles combine many features that would present challenges to defense systems designed to intercept ballistic missiles. (Indeed, a main reason that China and Russia have been developing hypersonic weapons is a desire to defeat the United States' comparatively advanced ballistic missile defense capabilities—both short-range terminal defenses that protect forces in a theater of operations and long-range midcourse defenses that protect the United States itself.) By spending much of their flight inside the atmosphere, hypersonic boost-glide missiles would have an advantage over ballistic missiles in surviving midcourse ballistic missile defense systems, which aim to intercept ballistic missiles in the middle of flight, when those missiles are high above the atmosphere on a predictable and detectable path. That potential advantage for hypersonic boost-glide missiles might become important if a potential U.S. adversary developed midcourse ballistic missile defenses that operated outside the atmosphere and that were effective against countermeasures (such as decoys to fool interceptor missiles).

Against shorter-range missile defenses, it is unclear how much advantage hypersonic missiles would have over ballistic missiles equipped with maneuverable reentry vehicles. By flying low, hypersonic missiles could force the surface-based radar associated with short-range defenses to detect a missile later in its flight, shortening the time available for a defense system to intercept it. But because hypersonic missiles use up much of their energy while gliding toward their targets, they are likely to be traveling more slowly than a ballistic missile's MaRV as it gets close to its target. In addition, both types of missiles can perform preprogrammed maneuvers near their targets to make it harder for short-range defenses to intercept them.

Hypersonic weapons also have the potential to create uncertainty about what their ultimate target is. Their low flight profile puts them below the horizon for long-range radar and makes them difficult to track, and their ability to maneuver while gliding makes their path unpredictable. Ballistic missiles equipped with MaRVs could also create target uncertainty by maneuvering during the late stages of flight. But because hypersonic missiles can maneuver during more of their flight, their target

uncertainty is greater than for a MaRV. Such uncertainty could be an advantage by making it harder for adversaries to defend against attacks, but it could also cause the target country or nearby countries to misinterpret the United States' intentions. The importance of that consideration would depend on the details of a particular scenario.

The United States does not currently field intermediate-range ballistic missiles, in part because some of those missiles were prohibited by the Intermediate-Range Nuclear Forces treaty, which the United States was a party to from 1988 to 2019. Over the years, however, the United States has mastered the technological challenges of operating such missiles. For example, in the 1980s, the U.S. military deployed Pershing II medium-range ballistic missiles with maneuverable warheads. Both the hypersonic missiles that DoD is currently developing and the ballistic missiles with MaRVs that CBO included in its analysis would probably be accurate enough to strike many fixed targets. However, both missiles would need improved targeting technology (such as a homing seeker or other type of sensor) to improve their accuracy or to enable them to strike moving targets.

Hypersonic boost-glide missiles would cost about one-third more than comparable ballistic missiles, in CBO's estimation. Specifically, CBO estimates that procuring 300 intermediate-range hypersonic boost-glide missiles like the ones being developed by the Army and the Navy and then sustaining the missile system for 20 years would cost a total of \$17.9 billion in 2023 dollars (see Table S-1). By comparison, 300 MaRV-equipped ballistic missiles with the same speeds, ranges, and targeting capabilities as those hypersonic missiles would cost a total of \$13.4 billion, CBO estimates. If potential adversaries developed effective midcourse defenses against ballistic missiles, the total cost for the ballistic missiles would be slightly higher because of the need to develop more advanced countermeasures to enhance the missiles' survivability.

Challenges Ahead for Hypersonic Missiles

Realizing the full potential of hypersonic weapons will depend on future success in achieving some of the improvements now being researched and developed, including missile components such as transparent communications windows that can withstand the high heat of extended flights. DoD is taking a phased approach to fielding hypersonic missiles. Early versions of those weapons will have capabilities at the lower end of the desired ranges and will not be able to locate targets autonomously or maneuver in response to attacks by

Table S-1.

Comparison of the Missile Options That CBO Analyzed

Option	Launch Mode	Estimated Range (Kilometers)	Average Speed Over Estimated Range (Mach number) ^a	Number of Missiles Purchased	Estimated Procurement Cost per Missile (Millions of 2023 dollars)	Estimated Cost of Option (Billions of 2023 dollars) ^b
Intermediate-Range Hypersonic Boost-Glide Missiles (Similar to LRHW/IR-CPS)	Land or ship	3,000	10	300	41	17.9
Intermediate-Range Ballistic Missiles Equipped With MaRVs	Land or ship	3,000	9	300	26	13.4
Medium-Range Hypersonic Boost-Glide Missiles (Similar to ARRW) ^c	Aircraft	1,000	7	300 100	15 18	5.3 2.2
Short-Range Hypersonic Cruise Missiles (Similar to HACM/HALO) ^d	Aircraft	Less than 500	7	n.e.	n.e.	n.e.
Short-Range Ballistic Missiles (Similar to SM-6 Block IB)	Land or ship ^e	Less than 1,000	6	300	6	3.5

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

CBO’s estimates are subject to significant uncertainty about the costs of less mature technology or components, which represent long-term investments in a wide range of research areas that are associated with high risks of cost and schedule overruns. These estimates represent one possible outcome based on the specific assumptions made about technologies and capabilities (see Appendix C for details).

ARRW = Air-Launched Rapid Response Weapon (being developed by the Air Force); HACM = Hypersonic Attack Cruise Missile (being developed by the Air Force); HALO = Hypersonic Air-Launched Offensive Antisurface Warfare missile (being developed by the Navy); IR-CPS = Intermediate-Range Conventional Prompt Strike missile (being developed by the Navy); LRHW = Long-Range Hypersonic Weapon (being developed by the Army); MaRVs = maneuverable reentry vehicles; n.e. = not estimated; SM = Standard Missile.

- a. “Mach number” refers to an object’s speed relative to the speed of sound in the air at sea level; for example, Mach 5 is five times the speed of sound.
- b. Consists of the costs to procure the missiles; the costs to integrate the missiles with existing platforms and to buy associated equipment, such as launchers; and the costs to sustain the missile system for 20 years. Costs to develop the missiles are not included.
- c. CBO estimated the costs of two versions of this option: one with 300 missiles, the same as the number of hypersonic LRHW/IR-CPS missiles in Option 1, and one with 100 missiles to reflect the fact that the air-launched weapons in this option would not need to be spread among ships and submarines in different parts of the world but could be stored in a few locations and flown to where they were needed on short notice. Thus, a smaller number of the air-launched hypersonic missiles in this option could provide a worldwide availability similar to that provided by the larger number of land- or sea-launched hypersonic missiles in Option 1.
- d. The Department of Defense is early in the process of developing this missile. Little is known about its characteristics, so CBO did not have a basis for estimating the cost of the missile.
- e. The SM-6 Block IB is being developed by the Navy as a variant of its existing Block IA ballistic missile. Although the new missile would primarily be a Navy weapon, reports indicate that the Army is also planning to use it.

missile defenses. However, those early hypersonic missiles may be able to carry out small maneuvers on preplanned trajectories to make them more difficult for defenses to track and intercept. Further enhancements would increase the risks of cost increases and schedule overruns.

What Are Some Limitations of CBO’s Analysis?

The models that CBO used to estimate missile performance are based on publicly available data and do not

incorporate classified technical specifications or the results of ongoing testing. To reflect uncertainty about current and likely future performance, CBO presents a range for its model results. In addition, CBO’s estimates of the costs of various missile options are derived from statements about planned inventories of hypersonic weapons by public officials and program offices. Large changes in the number of missiles purchased or problems in overcoming technical challenges could alter the relative costs of the options.



Chapter 1: Hypersonic Missiles and Their Policy Implications

A cornerstone of U.S. defense planning is the ability to establish and maintain freedom of military action anywhere around the globe if a crisis occurs. Such freedom of action is enabled by superior air and maritime forces that can neutralize defensive and offensive systems that adversaries could use to attack U.S. forces and prevent them from operating freely. Since the end of the Cold War, the United States has used its strategy of military superiority successfully against adversaries with limited military capabilities, at least during the initial combat phase of a conflict.

In recent decades, however, potential adversaries such as China and Russia have worked to diminish the United States' military advantage by developing advanced weapons with long ranges that could keep U.S. forces from operating in large areas—a strategy known as anti-access and area denial. With the Department of Defense shifting its focus from conducting counterinsurgency operations in the Middle East and elsewhere to deterring near-peer military competitors, the challenges of operating in an A2/AD environment have come to dominate DoD's planning.

Various approaches can be used to defeat A2/AD systems. One is to develop aircraft that have stealth characteristics that can help them elude air defenses (as the Air Force did during the Cold War and continues to do today by fielding F-35 stealth fighter aircraft and developing the B-21 stealth bomber). Another approach that DoD is taking now is to develop long-range, high-speed missiles that carry conventional (nonnuclear) weapons. Long range enables the missiles' launchers to stay out of reach of offensive A2/AD systems; high speed makes the missiles harder to intercept and lets them reach their targets more quickly from long distances. The Army, Navy, and Air Force are all developing hypersonic missiles, which can fly at speeds faster than Mach 5 (five times the speed of sound) in the atmosphere during much of their flight.

Besides concern about potential adversaries' A2/AD systems, another stated rationale for developing hypersonic missiles is the sense that the United States has fallen behind those adversaries in hypersonic missile technology. The United States has performed foundational research into the technological challenges of flying at hypersonic speeds since at least the 1950s. Over the decades since then, both U.S. allies and potential adversaries have also conducted research into hypersonic missiles. In recent years, advances in aerodynamics, materials science, and computational science have enabled them to make significant progress. Both Russia and China have announced in the past few years that they have developed and fielded hypersonic missiles. Russia is believed to have used a missile that it classified as hypersonic in its war with Ukraine.

The United States has not yet fielded such weapons, for both scientific and policy reasons. Hypersonic missiles are expensive, and there have been questions about the value of the capabilities they might provide. Achieving the desired performance for those weapons would require significant investment in additional research. Nevertheless, because of their potential, the U.S. military has established accelerated programs for hypersonic missiles, sharply increasing its support and funding, testing prototypes, and creating units in anticipation of fielding the weapons in the next few years.

Basics of Hypersonic Missiles

Missiles are considered to be hypersonic not only on the basis of their speed but also on the basis of their flight profile and means of control. The harshness of the environment around a hypersonic missile as it flies makes designing such missiles challenging. (For explanations of missile speeds and other terminology, see Box 1-1.)

What Is a Hypersonic Missile?

“Hypersonic” refers to speeds above Mach 5, or five times the speed of sound in air. (Although the speed

Box 1-1.

Missile Concepts and Terminology

Speeds

subsonic: less than the speed of sound in the air at sea level—that is, less than Mach 1 (767 miles per hour)

supersonic: from one to five times the speed of sound in the air at sea level—that is, Mach 1 to Mach 5 (767 miles per hour to 3,836 miles per hour)

hypersonic: more than five times the speed of sound in the air at sea level—that is, more than Mach 5 (3,836 miles per hour)

Ranges

short range: less than 1,000 kilometers (km, or 621 miles)

medium range: between 1,000 km and 3,000 km (621 miles to 1,864 miles)

intermediate range: between 3,000 km and 5,500 km (1,864 miles to 3,418 miles)

intercontinental range: more than 5,500 km (3,418 miles)

Miscellaneous Characteristics

responsiveness: a measure of a missile's ability to reach its target (cover its range) in a timely fashion

survivability: a measure of a missile's ability to not be intercepted en route to its target

conventional: nonnuclear

Types of Missiles and Components

ballistic missile: a missile that consists of a warhead and a guidance system mounted on a rocket motor (or booster). At launch, the booster propels the missile up and out of the atmosphere at high speed. Once the missile is above the atmosphere and the motor has shut down, the booster is jettisoned. The warhead then travels an unpowered, arcing path to its target, much like the path of a ball thrown up in the air (see the figure).

hypersonic missile: a missile that travels within the atmosphere (rather than above it) at speeds greater than Mach 5 and that can maneuver in the atmosphere for much of its flight. Hypersonic missiles can take various forms, such as boost-glide missiles or cruise missiles.

boost-glide missile: a missile that consists of a rocket motor, which accelerates the missile to a high speed, and a glide body containing a warhead. After the glide body detaches from the spent rocket, it uses its kinetic and potential energy, as well as lift generated by its movement through the air, to coast at high speed through the atmosphere and maneuver to hit its target.¹

cruise missile: a missile that typically flies at low altitudes (ranging from less than 100 meters for a subsonic cruise missile to about 30 km to 40 km for a hypersonic cruise missile) and that is powered throughout its flight. A hypersonic cruise missile is initially accelerated to speeds approaching hypersonic by a rocket booster, then accelerates and maintains speed throughout its flight using a jet engine called a supersonic combustion ramjet (or scramjet) that operates at speeds above Mach 4.

maneuverable reentry vehicle: a ballistic missile warhead capable of correcting its trajectory when it reenters the atmosphere, increasing its accuracy.

Types of Launch

air-launched: launched from aircraft in flight

ground-launched: launched from fixed or mobile (vehicle-based) launchers on land

sea-launched: launched from surface ships or submarines

Flight Phases and Paths

boost phase: the period from a missile's launch until its rocket booster shuts down. During the boost phase, the missile is powered by the rocket motor. The length of this phase depends on the desired speed of the missile when the booster shuts down. For intermediate-range missiles, the boost phase can last as long as two to three minutes.

1. Kinetic energy is a measurement of the energy that an object has because of its motion. Kinetic energy reflects the object's mass and speed. Potential energy is a measurement of the energy stored by an object—in this case, the energy that the object derives from being in a gravitational field. That energy reflects the masses of the Earth and the object as well as the object's distance from the Earth.

Continued

Box 1-1.

Continued

Missile Concepts and Terminology

midcourse phase: for a ballistic missile, the period from the end of the boost phase until the warhead reenters the atmosphere. During the midcourse phase, the warhead is coasting above the atmosphere on an arcing path. This phase is the longest part of a ballistic missile's flight. For intermediate-range ballistic missiles, it lasts roughly 10 minutes to 20 minutes.

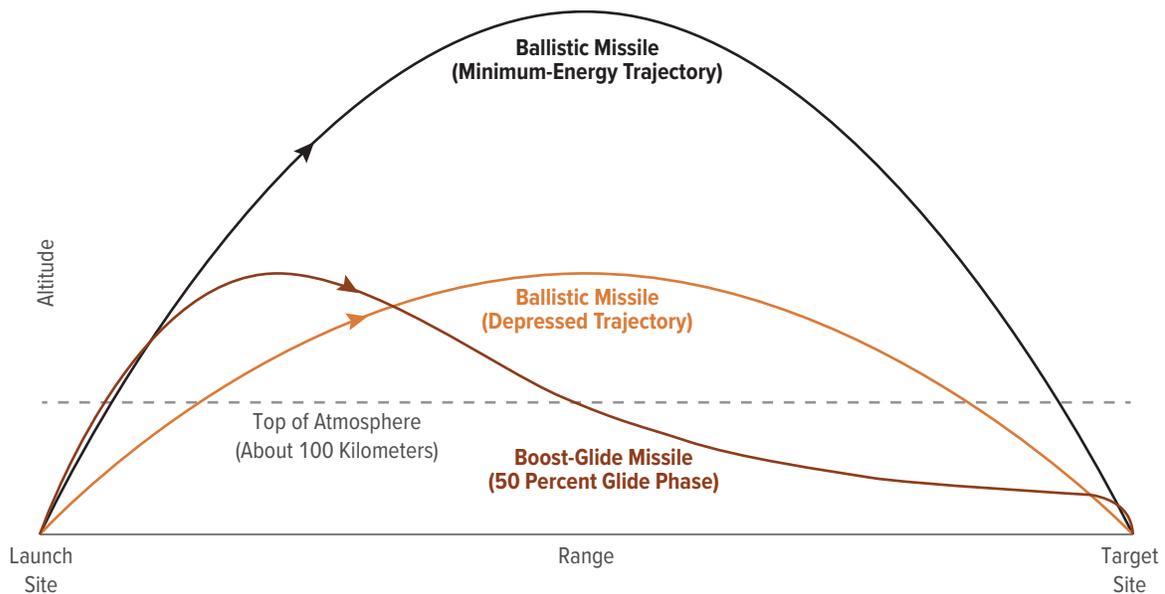
terminal phase: for a ballistic missile, the period from reentry into the atmosphere until the warhead reaches its target. This phase is very short, generally less than one minute.

glide phase: for a boost-glide missile, the period during which the glide body is coasting in the atmosphere. For the intermediate-range boost-glide missiles now being developed, the glide phase may last for 10 minutes to 20 minutes.

minimum-energy trajectory: the flight path that maximizes the range of a ballistic missile.

depressed trajectory: a lower, but still ballistic, path that shortens the flight time and reduces the range of a ballistic missile.

Notional Flight Paths for Different Ballistic and Boost-Glide Missile Trajectories With the Same Range



Source: Congressional Budget Office.

A missile's ballistic trajectory can be shaped in many ways. This figure shows a simple minimum-energy trajectory (MET) that is very close to a parabola, influenced mainly by gravity after the missile's rocket booster burns out. To depress the trajectory (lower the altitude), a ballistic missile could be launched at a shallower angle than the MET missile. To achieve the same range as the MET missile, the depressed-trajectory missile would require a larger rocket booster for a higher initial speed.

A boost-glide missile would start on a ballistic trajectory, but thrusters would be used in the first part of its flight to bring it back toward Earth sooner than in the ballistic flight. Control surfaces on the glide body would be used in the second part of the missile's trajectory to initiate gliding. The missile's maximum potential range would depend on its initial speed, the lift-to-drag ratio of the glide body, and the share of its trajectory that was spent inside the atmosphere.

of sound varies by altitude and depends on the density and temperature of the air, in most discussions of hypersonic weapons, that speed is measured at sea level under standard conditions, a convention that CBO uses as well.) Mach 5 is generally considered to describe an aerodynamic regime that is different from that of lower speeds—specifically, where heating becomes so significant that it dominates the physics of air flow around a moving object, such as an aircraft or a missile. For example, the transition between smooth flow and turbulent flow along the body of such an object becomes much more difficult to predict above Mach 5. That condition has implications for the heating of the object's surface and for the performance of aerodynamic control surfaces that allow the object to maneuver.

Thus, technically speaking, “hypersonic” refers only to travel at speeds above Mach 5 *within the Earth's atmosphere*, where interaction between the aircraft and molecules of air takes place. Spacecraft routinely travel at speeds well above Mach 5, and all but the shortest-range ballistic missiles also spend most of their flight at speeds above Mach 5 outside the atmosphere. But those flights are not considered hypersonic because they do not have the associated challenges of extended interactions with the air. Spacecraft or ballistic missiles that reenter the atmosphere near the end of their flight also face extreme heating at that point, but briefly. What distinguishes hypersonic missiles is that they have to contend with thermal effects throughout most of their flight.

Another defining characteristic of hypersonic missiles is that they depend on aerodynamic control surfaces (such as wings or tail fins) to glide and maneuver, like an aircraft, rather than using thrusters, like a spacecraft. Air is necessary for control surfaces to function, so a hypersonic missile must be within the atmosphere to maneuver.

The U.S. military is developing two types of hypersonic missiles: boost-glide missiles and cruise missiles. Both types need air to operate for reasons besides maneuvering. A hypersonic boost-glide missile consists of a rocket motor that accelerates the missile to a high altitude and speed and a glide body that detaches from the spent rocket. In addition to the kinetic and potential energy from its initial acceleration, the glide body uses lift generated by its movement through the air to extend its range and maneuver to hit its target (see Box 1-1 on page 6).

A hypersonic cruise missile is also initially accelerated to a high speed by a rocket booster. After that, it accelerates and maintains speed throughout its flight by using a type of jet engine known as a supersonic combustion ramjet (or scramjet). A scramjet uses oxygen from the air to burn its fuel, rather than carrying an oxidizer, as a rocket does, so it is known as an air-breather. Scramjets require supersonic air flow and only begin to operate at speeds above Mach 4. Although air-breathing engines tend to be smaller and lighter than rocket engines that carry both fuel and oxidizer, that size advantage is lessened by the size of the rocket booster used for the initial acceleration.

Design Challenges for Hypersonic Flight

For a missile traveling at hypersonic speeds in the atmosphere, the intense effects of heating during much of the flight influence every aspect of the missile's design. Heating creates the need for special materials to handle extreme temperatures for many minutes. It also affects the stability of the flight as well as communications and targeting for the missile.

Heating and Thermal Shielding. Moving at very high speeds within the atmosphere creates thermal challenges for an object such as a hypersonic glide body. The leading edge (the nose cone or the front edge of a wing) compresses the air ahead of the object, heating the air. The more rapidly the air is compressed, the hotter it will become. Drag also generates heat along any exposed surfaces, but to a lesser degree than air compression does. As the object moves through the heated air, its surfaces will begin to warm.

Structural materials for objects that travel at hypersonic speeds must be able to withstand high temperatures for the duration of the flight inside the atmosphere without significantly deforming or melting. The lower the heat tolerance of the material used to build the object, the greater the need for heat shielding, such as the ceramic plates used on the space shuttles that were operated by the National Aeronautics and Space Administration (NASA).¹ The choice of materials for an object's structure and heat shielding has a significant effect on the object's weight and cost.

1. The catastrophic effects that heating can have on an aircraft were dramatically illustrated in 2003, when an insulating tile on the Space Shuttle Columbia was damaged, causing the aircraft to overheat and break apart on reentry into the atmosphere.

Air behaves differently at different temperatures, which has major implications for the materials needed at those temperatures. As air warms, its molecules increasingly vibrate. At temperatures over 2,000 Kelvin (3,140° Fahrenheit), the air molecules can be ripped apart. And at temperatures above 4,000 K (6,740° F), the atoms from those molecules will lose some of their electrons (become ionized), and the surrounding gas will be in a plasma state. Plasma effectively absorbs radio frequency signals, affecting the ability to communicate or use radar.

DoD has suggested that, according to its modeling of the first-generation hypersonic boost-glide missiles it is developing, temperatures around most of the body of a missile are likely to remain within a range of 1,000 K to 2,000 K, below the threshold for plasma formation. Materials that have the potential to withstand those temperatures without melting or losing structural integrity include high-performance alloys known as superalloys. For the parts of a missile exposed to higher temperatures, exotic materials such as ceramic composites and materials made from carbon fibers, which have melting temperatures around 3,500 K, can be used. Carbon-carbon composites, such as those used on the space shuttle, have been shown to withstand heat of more than 2,000 K. Those high-performance materials are especially difficult and expensive to manufacture—factors that could limit the speeds and ranges at which hypersonic missiles can operate.

Flying at hypersonic speeds through the atmosphere for more than a few minutes presents challenges greater than those of reentering the atmosphere. Materials routinely used on reentry vehicles (such as ballistic missiles and the space shuttle) work over the shorter time frame associated with reentry to absorb heat or dissipate it through chemical processes. Such materials are not sufficient for hypersonic flight because they will eventually conduct heat inward or be used up.

Stability and Maneuvering. At speeds greater than the speed of sound (over Mach 1), a shock wave is produced ahead of a moving body, resulting in what is known as a sonic boom. When speeds reach the hypersonic regime (over Mach 5), the boundary between the shock wave and the moving body—the shock layer—can become very thin. In addition, the air near the moving body is very hot and can be chemically altered. One of the biggest challenges that designers of hypersonic missiles face is predicting the behavior of the shock layer. The

transition from smooth to turbulent air flow around a moving body can disrupt its stability and cause sudden, localized increases in temperature. High-speed computing has been fundamental to advancing understanding of that phenomenon in recent years.

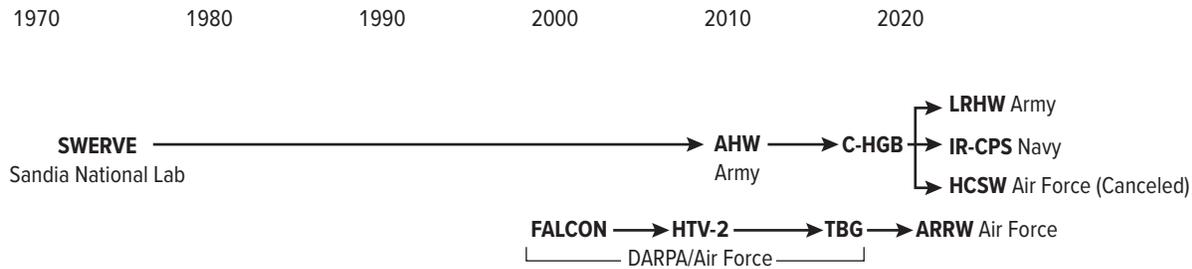
Maneuvers such as turns increase drag, adding to a missile's thermal load (the heat it experiences during flight, which is a function of temperature and time). Increased drag slows the missile considerably, reducing its range. Those factors tend to limit how much a hypersonic missile can maneuver.

Communications and Targeting. DoD has stated that its hypersonic boost-glide missiles will be able to emit and receive radio signals, such as those from the Global Positioning System (GPS). That statement implies that portions of a missile's glide body where transmitters and receivers are located will remain below the temperature threshold for plasma formation in the surrounding air, as DoD's modeling suggested might be the case. Even so, the intersection of materials, temperature, and communications remains a challenge in designing hypersonic missiles, as ongoing research by organizations such as the Defense Advanced Research Projects Agency (DARPA) has shown. Although the sensitive electronics necessary for communications must be adequately shielded from a missile's exterior temperatures, the missile needs to have windows (called radomes) through which signals can be emitted or received. The materials for such radomes are inherently difficult to develop because they must allow radio frequency or infrared radiation to pass through them while also providing significant thermal shielding.

Scramjet Technology. An additional challenge in developing hypersonic cruise missiles is designing engine components that can maintain proper air–fuel mixing at the right temperature, air pressure, and density for a supersonic combustion ramjet to operate for the duration of a missile's flight. That challenge has been likened to the difficulty of keeping a match lit in a hurricane. Before 2022, the United States had successfully operated a scramjet for only a few minutes. But the recent successful demonstration of a scramjet implies that several design challenges have been overcome. Nonetheless, engineering hurdles remain in the development of hypersonic cruise missiles, which must meet size, range, and speed requirements while also managing the thermal and aerodynamic challenges of hypersonic flight described above for boost-glide missiles.

Figure 1-1.

Progression of DoD's Research Programs for Hypersonic Boost-Glide Missiles



Data source: Congressional Budget Office.

AHW = Advanced Hypersonic Weapon; ARRW = Air-Launched Rapid Response Weapon; C-HGB = Common Hypersonic Glide Body; DARPA = Defense Advanced Research Projects Agency; DoD = Department of Defense; FALCON = Force Application and Launch From Continental United States; HCSW = Hypersonic Conventional Strike Weapon; HTV = Hypersonic Technology Vehicle; IR-CPS = Intermediate-Range Conventional Prompt Strike; LRHW = Long-Range Hypersonic Weapon; SWERVE = Sandia Winged Energetic Reentry Vehicle Experiment; TBG = Tactical Boost Glide.

A Brief History of U.S. Hypersonic Research

Research to overcome the challenges of hypersonic flight has been going on since World War II, when Germany developed the V-2, a ballistic missile that traveled faster than Mach 5 for part of its flight.² Soon after the war, the United States built its first wind tunnel for aerodynamic testing at hypersonic speeds and began developing its first intercontinental ballistic missiles. From 1959 to 1968, the United States test-flew a piloted hypersonic aircraft called the X-15, a research project that contributed to the development of NASA's piloted spacecraft. During that era, scientists made enough progress in aerodynamic design and advanced materials to address the challenges of extreme heating that ballistic missiles and spacecraft encounter briefly when they reenter the Earth's atmosphere. The greater challenges posed by extended flight and maneuvering through the atmosphere at hypersonic speeds and extreme temperatures remained the subject of active research programs.

Hypersonic flight continues to be extraordinarily challenging. But in recent years, computational science and materials science have advanced enough to transition to developing practical technologies for use in operational hypersonic missiles.

2. The V-2 is often considered to have made the first engineered flight at hypersonic speeds. But it was technically not a hypersonic missile, because it flew faster than Mach 5 within the atmosphere for only a small portion of its flight and because it did not use aerodynamic control surfaces to maneuver after its rocket stopped burning.

Technology for Hypersonic Boost-Glide Missiles

The modern era of DoD's involvement in research into hypersonic boost-glide missiles has roots in the Sandia Winged Energetic Reentry Vehicle Experiment (SWERVE) project, which began in the 1970s (see Figure 1-1). In 1985, the SWERVE project successfully tested a design for a missile glide body.

A second track of missile research began in 2003 when DARPA started the Force Application and Launch From Continental United States (FALCON) project. That project was designed to study technologies that would extend the reach of U.S. missiles so they could be launched from the continental United States rather than from locations closer to their targets.

In 2008, lawmakers established the Conventional Prompt Global Strike program to advance some of the technology originated by the FALCON project. The new program focused on a concept for an intercontinental-range hypersonic glider known as the Hypersonic Technology Vehicle-2. Reports at the time suggest that the program's rationale was to reduce the U.S. military's reliance on strategically located bases in multiple regions, for two reasons.³ First, strategic

3. See National Research Council, *U.S. Conventional Prompt Global Strike: Issues for 2008 and Beyond* (National Academies Press, 2008), <https://tinyurl.com/yjnfss59>; and Department of Defense, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, *Time Critical Conventional Strike From Strategic Standoff* (report of the Defense Science Board Task Force, March 2009), <https://dsb.cto.mil/reports/2000s/ADA498403.pdf>.

locations change over time, and they are not always known or available far enough in advance to allow the U.S. military to establish bases there. Second, growth in the size of adversaries' antiaccess and area-denial regions created a desire for long-range weapons that could destroy an adversary's air defenses and strike its mobile offensive systems early (or, in some cases, later) in a conflict.

Other technology under consideration for that mission included putting conventional warheads on some of the Navy's Trident missiles—long-range, submarine-launched ballistic missiles that were previously armed with nuclear warheads. The Conventional Trident Modification (CTM) program envisioned a nonnuclear warhead carried by a maneuverable reentry vehicle that would provide the greater accuracy that a conventional warhead requires to compensate for its much lower explosive power. The CTM program was first funded by the Navy in 2007. It was later canceled by lawmakers because of concerns that an adversary seeing a CTM launch might think the United States was launching a nuclear-armed Trident missile and might respond with a nuclear attack of its own. To avoid such confusion, the United States has generally maintained different types of missiles to carry nuclear warheads and conventional warheads.

After the CTM program was canceled, the Conventional Prompt Global Strike program continued working on the intercontinental Hypersonic Technology Vehicle-2, conducting test flights in 2010 and 2011. The second test in 2011 failed when contact with the vehicle was lost. After that, the program's funding was sharply reduced. In 2012, DoD began to shift its focus to shorter-range hypersonic missiles, and "global" was dropped from the program's name, which became simply Conventional Prompt Strike.

During the same period, the Army began the Advanced Hypersonic Weapon program, which built on the glide-body design of the earlier SWERVE project. The Advanced Hypersonic Weapon was successfully tested in 2011 but failed during the boost stage of a flight test in 2014.

Despite reductions in their funding after test failures, those early 21st-century programs led to the two main efforts that DoD is pursuing today to develop hypersonic boost-glide missiles:

- The Advanced Hypersonic Weapon evolved into the Common Hypersonic Glide Body. That glide-body design forms the basis for missiles that the Army

and Navy are developing, the Army's Long-Range Hypersonic Weapon and the Navy's Intermediate-Range Conventional Prompt Strike. (The Air Force also had a program based on the Advanced Hypersonic Weapon, known as the Hypersonic Conventional Strike Weapon, but it was canceled in 2020.)

- The Hypersonic Technology Vehicle-2 evolved into DARPA's Tactical Boost Glide vehicle, which forms the basis for the Air Force's current program to develop the medium-range Air-Launched Rapid Response Weapon.

Technology for Hypersonic Cruise Missiles

Research on supersonic combustion ramjet engines began in the 1950s. But the first successful flight test of a scramjet did not occur until 2002, when Australia's HyShot aircraft flew for a few seconds on a parabolic trajectory under scramjet power. Two years later, NASA's scramjet-powered X-43 successfully flew several tests in horizontal flight. The X-43 holds the record for the fastest jet-powered aircraft, having reached a speed of Mach 9.6 with the scramjet engine operating for 10 seconds during a flight test in 2004. Later development focused on the Air Force's X-51 program. A scramjet-powered X-51 aircraft was successfully flown in 2013 at Mach 5.1 for 210 seconds.

The research from those programs is being applied to several current efforts to develop an operational hypersonic cruise missile. Although scramjet technology appears to be maturing, integrating the engine into a missile that is small enough to be tactically useful will require significant further efforts. Trade-offs exist between speed, size, and range that might be addressed with improvements to fuel efficiency. Such improvements are being explored in laboratory testing and with modeling and simulation.

Much of the research into hypersonic cruise missiles being conducted worldwide is exploring the use of hydrogen fuel. Hydrogen has many characteristics that make it desirable for use in scramjets, such as high flammability and high caloric value (a measure of the energy that can be extracted during combustion). Hydrogen-fueled scramjets could theoretically operate at speeds higher than Mach 20.⁴ And many researchers

4. See P. Satyaprasad and others, "Missile Propulsion Systems," in N. Eswara Prasad and R. J. H. Wanhill, eds, *Aerospace Materials and Material Technologies*, vol. 2 (November 2016), pp. 305–330, https://doi.org/10.1007/978-981-10-2143-5_15.

prefer hydrogen to hydrocarbon-based fossil fuels for environmental reasons, because it produces only water as a byproduct. But hydrogen fuels also have downsides. Their extreme volatility increases safety concerns during the storage and handling of a missile, and their lower density than hydrocarbon fuels makes it harder to design a missile with the sort of range that DoD wants.⁵ For those reasons, DoD is likely to use hydrocarbon fuels in hypersonic cruise missiles, which would limit their maximum speed to about Mach 9.

DoD's Current Hypersonic Missile Programs

The Department of Defense has spent more than \$8 billion since 2019 on programs to develop hypersonic missiles. Those programs include separate efforts by the Army, Navy, and Air Force to develop hypersonic boost-glide missiles; collaborations among DARPA, the Air Force, and the Navy to research technology for hypersonic cruise missiles; and various research programs for missile components (discussed in Appendix A). In its latest five-year budget plan, the 2023 Future Years Defense Program, DoD is requesting \$13 billion over the 2023–2027 period for developing hypersonic missiles and almost \$2 billion for procuring missiles. (The procurement request represents only Army and Air Force programs; the Navy has not yet requested procurement funding for the hypersonic missile it is developing.)

This section describes DoD's major hypersonic missile efforts and the research, development, test, and evaluation (RDT&E) funding provided or requested for them. Those funding numbers are in nominal dollars, meaning that they have not been adjusted to remove the effects of inflation.

DoD has stated that the urgency of hypersonic missile development outweighs the need for traditional oversight, so its three boost-glide missile programs are proceeding outside the usual acquisition process, under an approach called rapid prototyping. The RDT&E funding described below for those programs is for advanced component development and prototypes (budget activity level 4) and, starting in 2023 for the Army's program, for system development and demonstration (budget activity level 5). In DoD's development strategy for hypersonic boost-glide missiles, the versions fielded initially will

have the capabilities of the prototype missiles. Full-capability versions will be fielded later.

The Army and the Navy are developing separate missile systems, but they are collaborating on a joint glide body for those missiles—the Common Hypersonic Glide Body, or C-HGB (see Figure 1-2)—and a common two-stage booster. The Navy is responsible for designing the glide body and the booster, and the Army is responsible for producing them. (The Air Force participated in that collaboration until 2020, when it chose to focus on a different glide-body design for its boost-glide missile.) The Army and Navy will use identical glide bodies but plan to separately develop different launch platforms for the missiles.

The Army's Long-Range Hypersonic Weapon

The Army's boost-glide missile, the Long-Range Hypersonic Weapon (LRHW), is intended to be launched from the ground using mobile transporter-erector-launcher (TEL) vehicles. An LRHW battery will consist of four TELs, eight missiles, and one operations center for the battery. Most of the performance characteristics of the LRHW are classified, but its range has been publicly stated as exceeding 2,775 kilometers (km, or about 1,724 miles).

The LRHW program has been funded since 2020 and has received \$1.7 billion through 2022. DoD requested \$807 million for the missile in 2023 (see Table 1-1). In that budget request, the Army estimated that RDT&E for the program would conclude in 2027, at a total cost of \$5.3 billion.

The LRHW program has completed successful flight tests of a prototype missile, but it has also experienced test failures in recent years. Several more flight tests, to be conducted jointly with the Navy, are scheduled through 2028. The Army expects to field initial prototype LRHW missiles in 2023 and two additional batteries in 2025 and 2027, respectively. DoD's 2023 budget request includes \$249 million in procurement funding to purchase LRHWs.

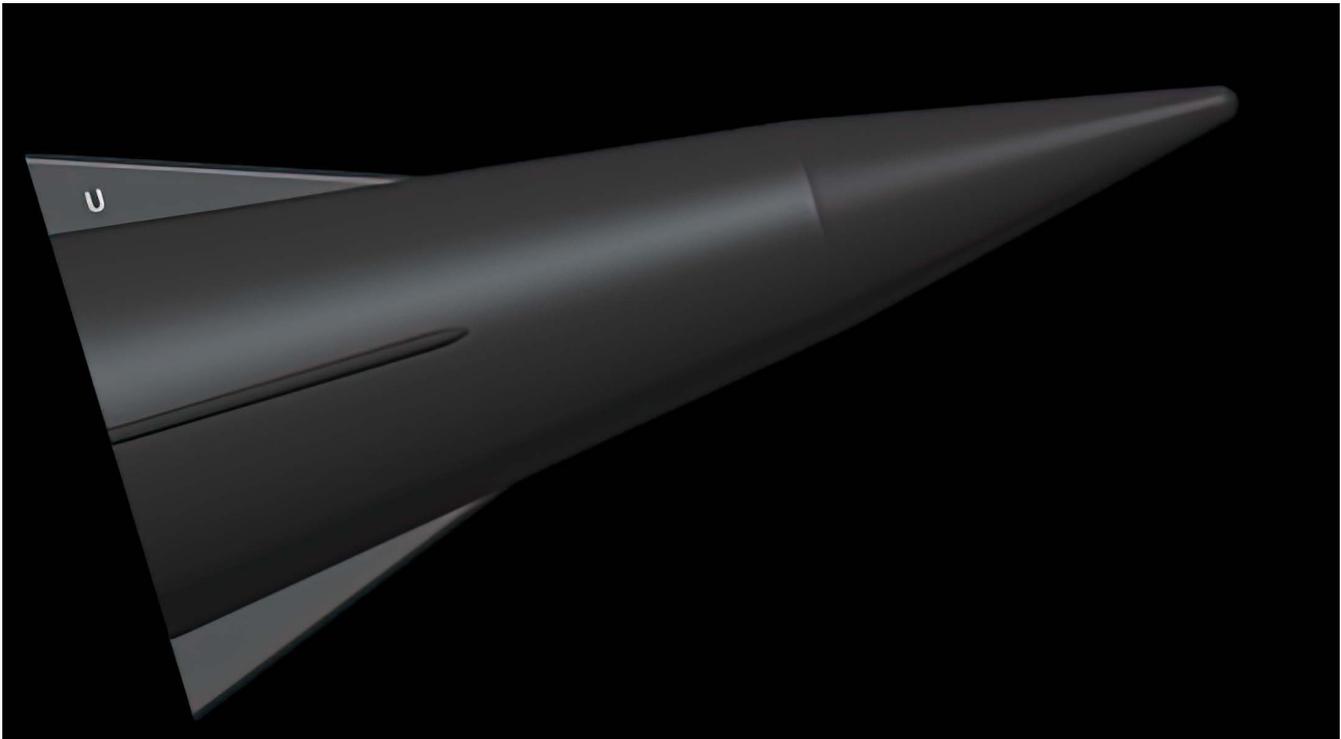
The Navy's Intermediate-Range Conventional Prompt Strike

The Navy's boost-glide missile, which will also carry the Common Hypersonic Glide Body, is a sea-launched missile called the Intermediate-Range Conventional Prompt Strike (IR-CPS). The Navy's original plan was to field the IR-CPS on Virginia class nuclear-powered submarines, using the Virginia payload module, a multimissile

5. See Gautam Choubey and others, "Hydrogen Fuel in Scramjet Engines—A Brief Review," *International Journal of Hydrogen Energy*, vol. 45, no. 33 (June 24, 2020), pp. 16799–16815, <https://doi.org/10.1016/j.ijhydene.2020.04.086>.

Figure 1-2.

Depiction of the Common Hypersonic Glide Body



Source: Army Rapid Capabilities and Critical Technologies Office (from a briefing to CBO on the hypersonic weapons budget, June 2020).

The Army and Navy are collaborating on the Common Hypersonic Glide Body (C-HGB). A glide body is the part of a hypersonic boost-glide missile that detaches from the spent rocket booster and glides to its target. Both services plan to use the C-HGB in the hypersonic boost-glide missiles they are developing: the Army's Long-Range Hypersonic Weapon and the Navy's Intermediate-Range Conventional Prompt Strike missile.

launcher that is planned to be built into newer versions of those submarines. To deploy the missiles sooner, the Navy now plans to field them on existing Zumwalt class destroyers first and then develop the launch capabilities for Virginia class submarines. The specifications of the IR-CPS are classified, but its range is expected to be about the same as that of the Army's LRHW (greater than 2,775 km).

The IR-CPS program has been funded by the Navy since 2019 and has received \$2.6 billion through 2022. DoD requested \$1.2 billion for the program in 2023. The Navy expects research and development on the IR-CPS to continue past 2027, at a total cost of more than \$9 billion.

The Navy's version of the boost-glide missile is expected to take longer to develop than the Army's version for several reasons. First, the timing of the IR-CPS was initially linked to the timing of the Virginia payload module. Second, launching a missile from a submarine requires

a "cold launch," in which the missile is ejected from the launch tube by a gas generator before the missile ignites. That process is more complicated than the "hot launch" used for ground-launched missiles such as the Army's LRHW. In a hot launch, the missile ignites and is propelled out of the launcher by its own exhaust.

The Navy had intended to demonstrate a prototype-capability IR-CPS in 2022, but the missile failed its first flight test in 2022. Joint flight tests with the Army are scheduled to continue through 2028. The Navy plans to demonstrate a cold-launch prototype in 2024, field prototype missiles on Zumwalt class destroyers in 2025, and field full-capability missiles on Virginia class submarines in 2028.

The Air Force's Air-Launched Rapid Response Weapon

The hypersonic boost-glide missile that the Air Force is developing, the AGM-183A Air-Launched Rapid

Table 1-1.

U.S. Hypersonic Weapons Programs and Their RDT&E Funding

Service or Agency	Program	Description	Estimated Range (Kilometers)	RDT&E Funding (Millions of nominal dollars)		Planned Initial Fielding Date
				Request for 2023	Total Past and Planned Funding ^a	
Army	Long-Range Hypersonic Weapon (LRHW)	Ground-launched boost-glide missile	3,000	807	5,269	2023
	Operational Fires	Ground-based launcher for hypersonic boost-glide missiles; uses the TBG and a tunable rocket motor for variable range	500	11	66	2023
Navy	Intermediate-Range Conventional Prompt Strike (IR-CPS)	Sea-launched boost-glide missile	3,000 ^b	1,205	At least 8,902 (continuing)	2025
	Hypersonic Air-Launched Offensive Antisurface Warfare (HALO)	Air-launched cruise missile	N.A.	92	At least 444 (continuing)	2028
Air Force	Air-Launched Rapid Response Weapon (ARRW)	Air-launched boost-glide missile	1,000	115	1,315	2023
	Hypersonic Attack Cruise Missile (HACM)	Air-launched cruise missile	500 ^c	462	1,812	N.A.
Defense Advanced Research Projects Agency	Hypersonic Air-Breathing Weapon Concept (HAWC)	Cruise missile technology	N.A.	60	At least 195 (continuing)	n.a. (Transitioned to the Air Force)
	Tactical Boost Glide (TBG)	Glide body prototype for ARRW	n.a.	30	At least 555 (continuing)	n.a. (Transitioned to the Air Force)
	Operational Fires	Ground-based launcher for hypersonic boost-glide missiles; uses the TBG and a tunable rocket motor for variable range	n.a.	N.A.	169	n.a. (Transitioned to the Army)

Data source: Congressional Budget Office, using Department of Defense data from the President’s budget request. See www.cbo.gov/publication/58255#data.

n.a. = not applicable; N.A. = not available; RDT&E = research, development, test, and evaluation.

a. Total RDT&E funding from the beginning of the program through the 2023–2027 Future Years Defense Program. Programs labeled “continuing” are expected to receive additional RDT&E funding after 2027.

b. The range of the Navy’s IR-CPS is expected to be about the same as that of the Army’s LRHW, which will use the same glide body.

c. The design details, including ranges, of HALO and HACM have not been made public. The range of a cruise missile depends largely on the amount of fuel it carries. Because of the Air Force’s stated intent to design HACM to be smaller than ARRW, CBO anticipates that the range will be about 500 kilometers. CBO has not evaluated whether HACM can achieve that range and still have a smaller size and lower weight than ARRW.



Figure 1-3.

Depiction of the Tactical Boost Glide Vehicle Being Carried by an ARRW Missile



Source: Air Force Air-Launched Rapid Response Weapon program office (Lockheed Martin illustration).

The Tactical Boost Glide (TBG) vehicle developed by the Defense Advanced Research Projects Agency forms the basis for the hypersonic boost-glide missile that the Air Force is developing, the Air-Launched Rapid Response Weapon (ARRW). The TBG is shown here as a slender, pointed object on the front end of the missile. The cone in the upper left of the drawing is the protective shroud from the front of the missile, which has just been ejected in preparation for releasing the TBG.

Response Weapon (ARRW), is based not on the Army and Navy's common glide body but on the Tactical Boost Glide (TBG) vehicle developed by DARPA (see Figure 1-3). The ARRW missile is designed to be launched from B-52 bombers, although there is discussion about using additional launch platforms, such as B-1 bombers. The Air Force has released some technical information about the missile: Its range will be at least 926 km (about 575 miles), and its booster will consist of a single-stage solid rocket motor.

The ARRW program received a total of nearly \$1.2 billion in RDT&E funding from 2019 to 2022. For 2023, DoD requested \$115 million for RDT&E and \$46 million for missile procurement. Separately, DARPA has spent \$555 million on the TBG program so far and requested \$30 million for 2023.

The first flight test of the current development effort was not successful, but it was followed by several successful flight tests. The Air Force's 2022 budget request

to purchase 12 ARRWs was cut by lawmakers, leaving questions about when and in what quantity the missiles will initially be fielded. The \$46 million procurement request for 2023 is intended to fund one missile.

Other Hypersonic Programs

Besides the military's three programs to develop hypersonic boost-glide missiles, the Army and DARPA are developing ground-based launchers for boost-glide missiles. In addition, the Air Force, the Navy, and DARPA are working on technology for hypersonic cruise missiles.

OpFires Launchers. The Army is continuing development work on DARPA's Operational Fires (OpFires) program, which demonstrated a flexible ground-based launch system for short-range hypersonic boost-glide missiles, capable of launching multiple payloads at a variety of ranges. OpFires has been funded through DARPA since 2018 and has received \$169 million through 2022. The Army spent a total of \$55 million on OpFires in 2021 and 2022 and requested \$11 million for 2023.

Budget documents indicate that the launch system will be fielded along with the LRHW in 2023.

Hypersonic Cruise Missiles. DoD is also developing hypersonic cruise missiles, which are based on scramjet technology. DARPA has been funding research on scramjets under the Hypersonic Air-Breathing Weapon Concept (HAWC) program since 2014; the program has received \$195 million through 2022. For 2023, DoD requested \$60 million for the program, whose name has been changed to MoHAWC. The Air Force and the Navy have both been collaborating with DARPA on scramjet research, and each service now has its own program to develop a hypersonic cruise missile.

The Air Force's effort, the Hypersonic Attack Cruise Missile (HACM) program, received \$190 million in 2022. An additional \$462 million was requested for 2023. The program is described in budget documents as aiming to achieve a long-range, prompt strike capability, building on technology developed through DARPA's HAWC program. Three companies received funding to develop a prototype HACM; two of the prototypes were successfully demonstrated in 2021 and 2022. The prototype developed by Raytheon and Northrop Grumman reportedly flew more than 500 km, but it is unclear how long the scramjet was operating during that flight.

The Navy was also involved in flight tests during DARPA's HAWC program. It requested \$92 million in 2023 for its own cruise missile development program: the Offensive Anti-Surface Warfare (OASuW) Increment 2, commonly known as the Hypersonic Air-Launched OASuW (HALO) program. Funding documents indicate that the Navy plans to field HALO missiles starting in 2028.

Design specifications for those various cruise missiles have not been publicly released. For a hypersonic (or any) cruise missile, design trade-offs exist between speed, size, and range.

The Path Forward for U.S. Hypersonic Missiles

In addition to the programs discussed above, DARPA and the laboratories of the military services are funding many research programs related to hypersonic flight. The topics of that research provide insights into the technological challenges that remain in fielding hypersonic missiles. For example, many of those research programs seek to develop technical knowledge or components that

will increase the range or payload of hypersonic missiles or enhance the ability to control them for maneuvering and targeting. (For more details about those programs, see Appendix A.)

DoD has stated that the hypersonic missiles currently in development will be developed and fielded in stages. The existence of ongoing research efforts to increase the range, maneuverability, and targeting capabilities of the next generation of hypersonic missiles suggests that the initial versions fielded by DoD will lack some of the performance and features often attributed to hypersonic missiles. As a result, it appears likely that DoD's first generation of hypersonic weapons will operate at or below the minimum ranges associated with the range categories for missiles (see Box 1-1 on page 6). For instance, intermediate-range missiles are defined as reaching between 3,000 km and 5,500 km, but the range of the Army's and Navy's intermediate-range hypersonic boost-glide missiles (LRHW and IR-CPS) is expected to be about 3,000 km because heating will limit the speeds those missiles can sustain.

Thermal challenges also suggest that those missiles will be limited in what maneuvers they can perform, because their trajectories will be designed to minimize thermal stresses on the missiles. Furthermore, DoD's first-generation hypersonic missiles are not expected to have the accuracy or sensors needed to operate effectively in situations in which targets may be moving.

Policy Issues Related to Hypersonic Missiles

As significant progress has been made on the development of hypersonic missiles over the past decade, support for such weapons appears to have broadened in the United States. Potential reasons include the rise of China as a technological and military power, the pivot in U.S. defense policy toward a greater focus on China and Russia as near-peer competitors, and announcements by those two countries that they have overcome technological challenges and fielded hypersonic missiles. Nevertheless, hypersonic missiles could be seen as costly and unnecessary given the diverse arsenal of strike weapons that the U.S. military already possesses and given the immature state of potential adversaries' defenses against current U.S. missiles. Ultimately, whether hypersonic missiles are affordable and useful will depend on whether remaining technological hurdles can be overcome and at what cost.

Beyond general considerations of usefulness and cost—which would apply to any new weapon system—other policy issues are specifically associated with deploying hypersonic missiles. The most prominent of those issues involve hypersonic missiles’ potential to confuse adversaries about the United States’ nuclear intentions and their potential to escalate crises.

Nuclear Ambiguity

Nuclear ambiguity occurs when an adversary is uncertain about whether an incoming missile is armed with a nuclear or a conventional warhead. That uncertainty can lead the adversary to respond with nuclear weapons if it thinks it may be coming under a nuclear attack. The desire to avoid a nuclear response to a conventional strike is a significant, widely agreed upon principle of U.S. security policy. The Navy’s Conventional Trident Modification program of the early 2000s was canceled largely because lawmakers were concerned that a Trident missile armed with a conventional warhead would be indistinguishable from one armed with a nuclear warhead.

Although the U.S. military has generally used different missiles for conventional and nuclear warheads, there is precedent for fielding nuclear and conventional versions of the same or very similar missiles. Examples include the Navy’s Tomahawk Land Attack Missile and the Air Force’s Air-Launched Cruise Missile. During the Conventional Trident Modification program, methods were proposed to ensure that adversaries could distinguish conventional from nuclear Tridents. Those proposals included having the conventional missiles use a different trajectory and maneuvering capabilities that would keep them from flying over countries other than the United States and the intended target.

Crisis Instability

Regardless of ambiguity about the nature of a missile’s payload, the compressed time frames associated with a strike by a conventional hypersonic missile could be seen as fundamentally destabilizing during a conflict. A missile capable of flying 3,000 km in only about 15 minutes would allow little time for an adversary to make a well-thought-out response. The same issue would exist with conventionally armed ballistic missiles because their travel times would be similar to those of boost-glide missiles.

In addition, the maneuverability of hypersonic missiles creates uncertainty about their targets. When a ballistic missile is launched, despite its extreme speed, its general destination is roughly calculable—both because its high trajectory makes it observable to powerful terrestrial radar (as explained in Chapter 3) and because its ability to change its path after its rocket booster burns out is limited. A ballistic missile equipped with a maneuverable reentry vehicle probably could maneuver by no more than several tens of kilometers after reentering the atmosphere, whereas a hypersonic boost-glide missile could theoretically strike largely undetected anywhere within a radius of several thousand kilometers.

A hypersonic boost-glide missile would probably be detected at launch (if the adversary had space-based infrared sensors with the ability to do so and in the correct position). But the difficulties of tracking the boost-glide missile through its lower-altitude flight, combined with its much greater ability to change direction, mean that potential adversaries might not know whether they or another country in the region was the intended target. That target uncertainty could increase the likelihood of a response (accidental or otherwise) before the actual nature of the attack was known.

Chapter 2: Scenarios That Define Potential Requirements for Hypersonic Missiles

The U.S. military's arsenal includes a wide variety of guided weapons that can be used to attack targets on land. Those weapons have ranges that vary from as short as a few kilometers (for the Joint Direct Attack Munition) to more than 1,500 kilometers (for the Tomahawk cruise missile) and speeds that vary from well below the speed of sound (for the AGM-154 glide bomb) to more than three times the speed of sound (for the Army Tactical Missile System). With that variety available, why is the Department of Defense interested in pursuing new and relatively expensive hypersonic missiles?

Longer ranges and higher speeds are the main attributes that distinguish the hypersonic weapons DoD is developing from the conventional strike weapons in today's inventory. Long range and high speed are nearly always desirable characteristics for a strike weapon, but they can be expensive. DoD's shift in focus, to potential conflicts with near-peer adversaries that have advanced militaries, has brought those characteristics to the fore. Of specific concern are potential conflicts with China or Russia, both of which have advanced air defenses, long-range bombers and missiles, and antiship missiles. With those systems, Chinese or Russian forces could establish large areas in which U.S. forces would be vulnerable to attack.

Such an antiaccess, area-denial strategy would reduce U.S. combat power and give an adversary greater freedom of action. In particular, the A2/AD weapon systems that China and Russia have deployed could force the U.S. military to use ground- or ship-launched weapons from as far as 4,000 km (about 2,500 miles) away and air-launched weapons from at least 1,000 km (about 600 miles) away. Launching such weapons from shorter distances would put the launchers and the units operating them at greater risk. Long-range weapons with high speeds could be launched from areas of lower risk but not take too much time to cover the longer distances to their targets.

This chapter describes, in general terms, the planning scenarios for near-peer adversaries that DoD is currently

using and their implications for the performance requirements of weapons designed to overcome the A2/AD threats found in those scenarios. In any conflict, combatants try to establish A2/AD zones to protect their own forces and territory and to limit where their opponents can safely operate. But near-peer adversaries pose particular A2/AD challenges because they are likely to possess longer-range weapons (and the ability to target them) in greater numbers than less advanced adversaries do. In particular, China and Russia both have many offensive and defensive weapon systems capable of establishing challenging A2/AD environments.¹ Beyond those challenges, other types of scenarios could also affect the U.S. military's requirements for hypersonic missiles.

China

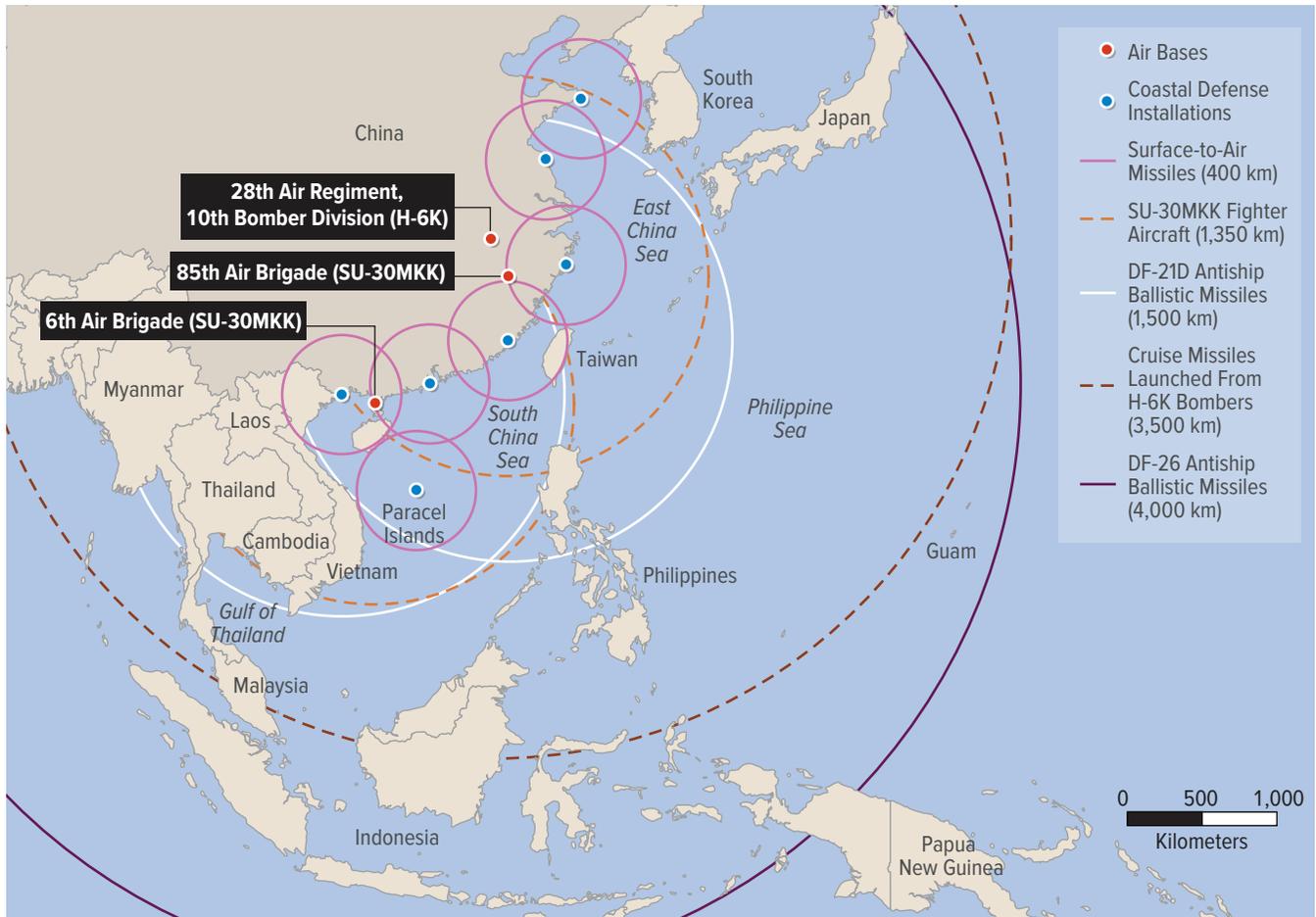
Disputes over territory in the South China Sea have occurred in recent years. The People's Republic of China has threatened at times to take the island of Taiwan by force. And the United States has indicated in increasingly explicit ways its intent to come to Taiwan's aid should China attempt to do so. In addition, if the Chinese military tried to coerce other U.S. allies in the Pacific or shut down access to sea lanes there, the United States could choose to respond militarily.

If a conflict erupted in the region, China has a variety of A2/AD weapons that could pose challenges to the United States and its allies. At present, China's antiship and air defenses have the potential to limit U.S. naval and air access to much of the South China Sea, particularly because China could extend the reach of those weapons by basing them on disputed islands in the South China Sea, such as those in the Paracel and Spratly chains. Chinese surface-to-air missiles and antiship cruise missiles located on the mainland could cover an area with an estimated radius of 400 km, potentially including Taiwan

1. For more discussion of scenarios involving Russia and China, see Congressional Budget Office, *Options for Fielding Ground-Launched Long-Range Missiles* (February 2020), www.cbo.gov/publication/56068.

Figure 2-1.

Approximate Coverage Areas of China’s Potential A2/AD Defenses



China has been developing a variety of weapon systems designed to keep U.S. and U.S. allies’ forces far away from its coasts. In a potential conflict with China, those A2/AD systems could be targets for U.S. hypersonic missiles or alternatives.

Data source: Congressional Budget Office.

The weapon systems that make up China’s A2/AD zone include air- and missile-defense systems that are assumed to cover China’s coastline. Some air-defense sites might also be launch sites for antiship ballistic missiles; those launchers are potentially mobile. China’s military airfields, where fighter aircraft and bombers that could launch cruise missiles are based, are generally located farther inland. Basing those A2/AD systems on Chinese-occupied islands in the South China Sea would extend their coverage areas.

A2/AD = antiaccess and area-denial; km = kilometers.

(see Figure 2-1). If those missiles were located on the Paracel Islands—which China has claimed sovereignty over, in violation of international law—China’s reach into the South China Sea could be roughly doubled.

In addition, Chinese DF-21D antiship ballistic missiles have a range of 1,500 km. DF-26 antiship ballistic missiles may reach as far as 4,000 km, but their actual capabilities are not yet clear and would require that China

have an intelligence and surveillance system that could detect and track targets at those long ranges with enough accuracy for the missiles to find their targets. Chinese H-6K bombers flying from an inland base could reach 3,500 km offshore, and SU-30MKK fighter aircraft have a range of 1,350 km.

China also employs modern air defenses, most of which were purchased from Russia or designed in Russia and

licensed for production in China. The most notable are the S-300 and S-400 surface-to-air missile systems, which have maximum ranges of a few hundred kilometers. China has also fielded a variety of shorter-range air-defense systems that could engage naval aircraft in the region or land-based fighters and bombers. Those defenses would be less effective against cruise missiles, such as the Tomahawk, that fly a few hundred feet above the surface to avoid detection until they are close to their targets. But such defensive systems would still have some capabilities against low-flying missiles at short ranges.

To defend against ballistic missiles, China's S-300 and S-400 surface-to-air missile systems (like the U.S. Patriot missile system) have some capability as point defenses against shorter-range ballistic missiles as they approach their targets. (A point defense can protect a relatively small area, from a few kilometers to a few tens of kilometers in diameter.) China is working to develop interceptors to defend against longer-range ballistic missiles, but those systems are still in development and have not yet been deployed. Thus, China's ability to intercept very fast, high-flying missiles en route to their targets is likely to be limited for at least the near future.

Russia

As evinced by its invasion of Ukraine, Russia may harbor aspirations to restore the territory of the former Soviet Union. That territory includes the three Baltic Sea nations of Estonia, Latvia, and Lithuania, which are now members of the North Atlantic Treaty Organization (NATO).² If Russia invaded a NATO country, the United States would have a treaty-based obligation to respond. Such a response would be harder if Russian forces were able to establish a strong ground presence in one of those NATO countries and could protect themselves with long-range air defenses and missile attacks.

2. As of this writing, Russia is engaged in a protracted war in Ukraine. Depending on the outcome of that conflict and its effects on Russia and NATO, and the likely expansion of NATO to include Finland and Sweden, the set of Russia scenarios could expand to include direct attacks on other NATO countries. However, the basic characteristics of an A2/AD environment and the weapons that might be needed to address it are likely to remain roughly the same, although the likelihood of a conflict with Russia could rise or fall.

Like China, Russia has a variety of antiaccess and area-denial weapons that could pose challenges for the United States and its allies—particularly Russia's long-range missiles and air defenses. For attacking targets on land, Russia can use ground-launched Iskander ballistic missiles, which have a range of 300 km, and ground-, ship-, and air-launched land-attack cruise missiles, which have ranges up to several thousand kilometers. In addition, Russia's Kinzhal ballistic missiles, which have a range of 2,720 km when launched from fighter aircraft, can be used to strike targets on land or at sea and could limit naval access to the Baltic Sea. And Russia's air defenses, such as the S-300 and S-400 surface-to-air missile systems also deployed by China, could limit access by NATO air forces to areas that would include much of Poland, Lithuania, Latvia, Estonia, and Finland (see Figure 2-2).

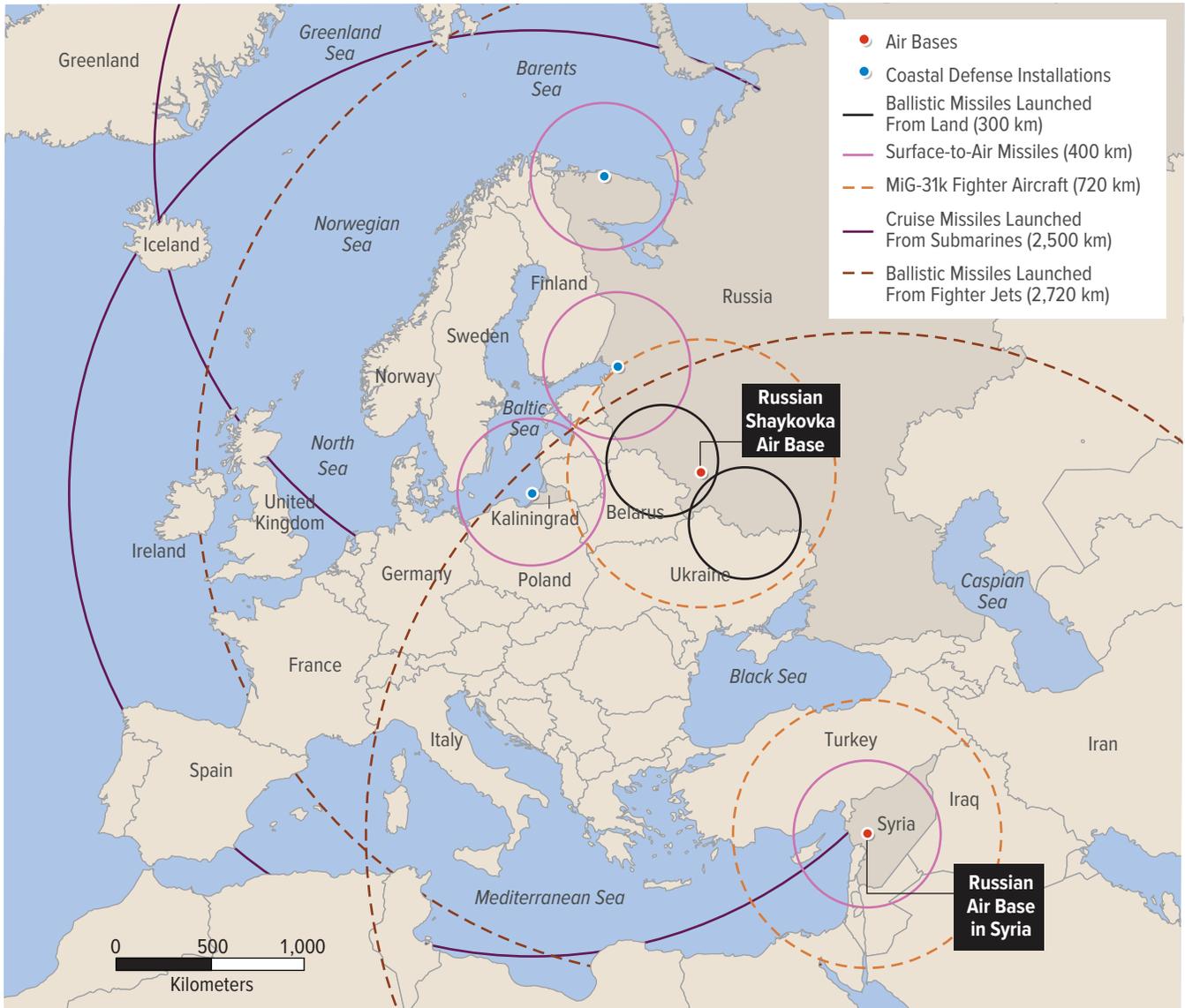
However, the Russian military's failure to seize the Ukrainian capital of Kyiv in February 2022, which many analysts thought would be fairly easy for Russia, suggests some of the pitfalls of relying on technical assessments to measure military capability. Sensors, intelligence gathering, flexible command-and-control systems, and well-trained personnel are just as important. Thus, the risks to U.S. weapon systems in potential adversaries' A2/AD zones may be overstated.

Other Scenarios

Hypersonic weapons could prove to be useful in ways other than thwarting the A2/AD defenses of near-peer adversaries. Notable examples would be scenarios in which the United States wanted to conduct a rapid, long-distance strike because it had intelligence indicating the location of a high-value target, such as the leader of a terrorist organization or a nuclear-armed missile about to be launched by a rogue nation. Such intelligence would have to be acted on quickly because of potential movement of the target. Although there might not be U.S. forces nearby, a hypersonic missile could potentially hit the target from a long distance in a time frame that would not be possible with a slower-flying missile, such as a subsonic cruise missile. That type of mission is what initially revived DoD's interest in hypersonic weapons in the early 2000s.

Figure 2-2.

Approximate Coverage Areas of Russia’s Potential A2/AD Defenses



Russia has been developing weapon systems that could keep U.S. and NATO allies’ forces far away from its borders. In a potential conflict with Russia, those A2/AD systems could be targets for U.S. hypersonic missiles or alternatives.

Data source: Congressional Budget Office.

Russian A2/AD systems are made up of air- and missile-defense systems strategically located in coastal and inland locations, covering much of Europe and nearby waterways. Basing those systems outside mainland Russia, such as in Syria and Kaliningrad, would extend their coverage areas.

A2/AD = antiaccess and area-denial; km = kilometers; NATO = North Atlantic Treaty Organization.



Chapter 3: Comparing the Capabilities of Hypersonic Missiles and Potential Alternatives

Considering the scenarios described in Chapter 2, the Congressional Budget Office analyzed how well different types of weapons could conduct rapid strikes with conventional warheads in an antiaccess and area-denial environment. In such an environment, three characteristics that are particularly important for strike weapons are range, responsiveness, and survivability: To be effective, a strike weapon must be able to reach the target (range) in a timely fashion (responsiveness) with a reasonable probability of not being intercepted en route (survivability). A strike weapon's range, responsiveness, and survivability for a given mission are a function not only of the weapon's performance but also of the type of platform that launches it. The performance of the opponent's weapons plays a role as well.

CBO used the metrics of range, responsiveness, survivability, and overall effectiveness in an A2/AD environment to characterize the potential performance of the following general types of weapon systems:

- Hypersonic boost-glide missiles;
- Ballistic missiles with various ranges and trajectories;
- Subsonic, supersonic, and hypersonic cruise missiles; and
- Long-range bomber aircraft.

Using the results of that general performance comparison, CBO created five illustrative options with specific quantities of particular weapon systems and compared the potential costs and effectiveness of those options (see Chapter 4).

The performance characteristics of the hypersonic missiles that the Department of Defense is developing are not publicly available, so CBO conducted its analysis by modeling generic versions of each type of weapon system using information that has been made public.

The technologies of the systems CBO analyzed exist in various states of maturity. But for the purposes of comparing performance, the systems were all assumed to be mature enough to deploy in the near future.

CBO concluded that although the hypersonic missiles now in development would theoretically have the energy to glide farther than a ballistic missile with the same initial speed, heating of the missile body would probably limit the range at which those hypersonic missiles could operate. Consequently, the hypersonic boost-glide missiles and cruise missiles currently being developed would have to be located near or within an A2/AD zone to conduct rapid strikes.

Hypersonic boost-glide missiles and ballistic missiles are considerably faster than the other weapons that CBO examined, including hypersonic cruise missiles. CBO concluded that over short to intermediate ranges, hypersonic boost-glide missiles might be slightly faster than ballistic missiles of the same range that were flying on a minimum-energy trajectory (a flight path that maximizes the range of a ballistic missile). But hypersonic boost-glide missiles would be no faster than ballistic missiles flying on a lower, or depressed, trajectory (which would require a little more power to achieve the same maximum range as a ballistic missile flying on a minimum-energy trajectory).

A purely ballistic missile with a conventional warhead would not be accurate enough for many targets, so the notional ballistic missile that CBO included in this comparison would be equipped with a maneuverable reentry vehicle capable of correcting its trajectory when it reentered the atmosphere. MaRVs would probably give ballistic missiles an accuracy similar to that envisioned for the hypersonic missiles DoD is developing (although those ballistic missiles would not be capable of flying the nonballistic trajectories used by hypersonic boost-glide

missiles). Maneuverable reentry vehicles are a less challenging technology than hypersonic glide bodies; they have been studied since the 1960s and were deployed on the U.S. military's intermediate-range Pershing II nuclear-armed missiles in the 1980s.

In terms of performance against defenses, CBO's analysis found that subsonic cruise missiles are among the most difficult munitions to detect because they are small and fly close to the ground. But once detected and tracked, they are easier to intercept than missiles traveling at higher speeds. For all types of missiles, as speed increases from subsonic to hypersonic, the challenge of intercepting them increases.

The ability of hypersonic boost-glide missiles and ballistic missiles with MaRVs to avoid being detected and intercepted varies with the type of defense system—specifically, with the phase of a missile's flight in which it is targeted by the defense system. (For a description of those phases, see Box 1-1 on page 6.) A hypersonic boost-glide missile may be detected by infrared sensors during portions of its boost phase as well as in its glide phase, when its temperature increases. The missile can also be detected by ground-based radar during early parts of its trajectory, when it is relatively high in the atmosphere, and at later stages, when it is closer to the radar.

Tracking and intercepting a missile in the middle of its flight would be considerably harder with hypersonic boost-glide missiles than with ballistic missiles. But the inherent challenges of ballistic missile defense—coupled with the fact that no potential U.S. adversaries have yet deployed midcourse defense systems—suggest that the advantages offered by hypersonic missiles against such long-range defenses may not be important at this time. Moreover, modifying a ballistic missile's trajectory (such as depressing its altitude) or using countermeasures (such as decoys to fool interceptor missiles) would make ballistic missiles difficult to counter even if potential adversaries deployed midcourse defenses.

Against defenses that target missiles in the terminal phase of their flight, ballistic missiles with MaRVs and hypersonic boost-glide missiles would probably be similarly effective because both would be able to maneuver as they got close to their targets.

Range

The threats that an A2/AD environment poses to missile launchers increase the importance of range for missile systems. Most of the missiles that the United States is deploying or developing for those purposes today have ranges of 5,500 kilometers (about 3,400 miles) or less, with the exception of long-range nuclear delivery systems, such as submarine-launched Trident missiles and ground-launched Minuteman III missiles (see Table 3-1). For any weapons with a range of less than 5,500 km, the ability to position launch platforms in proximity to a conflict but outside the range of an adversary's defenses is important. The defenses that China, Russia, or a regional power might use to threaten U.S. weapons and their launchers could have ranges from 400 km to 4,000 km (about 250 miles to 2,500 miles), depending on the type of defense.

In a China scenario, for example, a U.S. missile with a range of 3,000 km (like the Army's planned Long-Range Hypersonic Weapon) would be able to reach China's populous and militarily important coastal regions if it was launched from the Pacific island of Guam. But in doing so, it would be within range of China's medium-range bombers and ballistic missiles (see Figure 2-1 on page 20). Whether those Chinese weapons could destroy the missile launcher would depend on how it was deployed (dispersed, camouflaged, or dug in), how well it was protected by air and missile defenses, and how quickly its missiles were launched at the start of a conflict.¹ The fate of the launcher would also depend on the accuracy and effectiveness of China's weapons, the number of long-range missiles in China's inventory, and the ability of China's intelligence and command-and-control systems to pinpoint the launcher's location.

A U.S. Navy ship carrying a weapon similar to the planned Intermediate-Range Conventional Prompt Strike missile might have to stay as far as 4,000 km away from China's coast if China was able to track the ship and if its DF-21D or DF-26 antiship ballistic missiles proved effective at that range. In such a case, the IR-CPS missile might not be able to reach targets on China's

1. To protect the U.S. military's ability to launch a strike, missile launchers can be deployed in greater numbers than the minimum necessary for the strike and can be positioned in separate areas (dispersed), hidden by blending into the surroundings (camouflaged), or hidden under the ground (dug in).

Table 3-1.

Ranges of Various U.S. Weapon Systems

Type of Weapon System	Example	Range (Kilometers)
Existing Weapons		
Ground-launched tactical ballistic missile	Army Tactical Missile System (ATACMS)	300
Subsonic cruise missile	Tomahawk	1,000 to 2,400 ^a
Submarine-launched ballistic missile	Trident	7,400
Ground-launched ballistic missile	Minuteman III	13,000
Supersonic stealth fighter aircraft	F-22 Raptor	1,500 ^b
Subsonic stealth bomber	B-2 Bomber	4,800 ^b
Weapons Under Development		
Intermediate-range hypersonic boost-glide missile (Ground- or sea-launched)	Long-Range Hypersonic Weapon (LRHW)/ Intermediate-Range Conventional Prompt Strike (IR-CPS) prototype	3,000 ^c
Medium-range hypersonic boost-glide missile (Air-launched)	Air-Launched Rapid Response Weapon (ARRW) prototype	1,000 ^d

Data source: Congressional Budget Office, using data from the Department of Defense. See www.cbo.gov/publication/58255#data.

DoD = Department of Defense; km = kilometers.

- The standard variant of the Tomahawk missile has a range of roughly 1,000 km. The longest-range variant is reported to have an operational range of up to 2,400 km.
- This range is the unrefueled combat radius, which reflects an assumption that the aircraft has sufficient fuel to return to base. Range can be extended if the aircraft is refueled in flight.
- DoD has released information suggesting that the LRHW and IR-CPS missiles will have a range of at least 2,775 km. CBO used 3,000 km for its estimate.
- This range is an estimate based on the lower boundary of the range stated by DoD.

coast, although it could still attack air-defense systems and other fixed targets deployed on artificial islands that China has built in the South China Sea. The IR-CPS might also be used against Chinese surface ships if they were not moving. However, a submarine carrying that missile could use its stealth capabilities to get closer to China's coast and strike targets there or perhaps farther inland. Subsonic cruise missiles like the Navy's Tomahawk might also be effective in that scenario.

The hypersonic boost-glide missile that CBO modeled on the Air Force's planned Air-Launched Rapid Response Weapon has a much shorter range than the Army's and Navy's boost-glide missiles—about 1,000 km—which would require an aircraft carrying it to get much closer to China's coast. China's air-defense systems have much shorter ranges than its bombers and ballistic missiles, about 400 km. But Chinese fighter aircraft (like the SU-30MKK) armed with air-to-air missiles might be able to attack U.S. aircraft as far as 1,000 km from the coast. ARRW missiles launched from that distance could probably still reach coastal targets.

In a Russia scenario focused on the Baltic region, ground-based missile launchers could be located at multiple spots in nearby North Atlantic Treaty Organization countries, but they might require some protection. Submarines would be less likely to play a role in that scenario than they would in the waters around China because the Baltic Sea is smaller and space would be constrained. Aircraft, particularly ones with stealth characteristics, might be able to approach Russia's borders and launch missiles at inland targets.

In the face of A2/AD challenges from such potential adversaries, the United States could use a phased approach to destroying A2/AD systems. For example, if ships, submarines, and bombers were not yet in position, ground-based weapons that had already been deployed to a region could be fired the most quickly. The locations where such weapons could be deployed are limited in the Pacific region but are more numerous in the Baltic region. At present, U.S. allies in the Pacific have not agreed to allow the United States to base its planned hypersonic missiles in close proximity to China, leaving

Guam as the most likely launch location. In Europe, by contrast, most if not all NATO countries might serve as launching points for U.S. missiles. Even with a range limited to 3,000 km, a missile like the Army's Long-Range Hypersonic Weapon might be able to degrade enough of the air and missile defenses in a small area early in a conflict to allow U.S. aircraft to operate in that area. In turn, those aircraft could use air-launched hypersonic missiles to eliminate additional A2/AD sites, further opening the area to U.S. shorter-range forces.

Intermediate-range ballistic missiles equipped with maneuverable reentry vehicles would have the same, if not longer, range than the hypersonic boost-glide weapons that CBO modeled. The reason is that a MaRV is likely to be lighter than a hypersonic glide body. An air-launched ballistic missile with a MaRV could be boosted by a single-stage rocket, similar to that of the hypersonic ARRW. With a lighter payload, such a missile's range could exceed that of the ARRW. Alternatively, the payload capacity of a MaRV-equipped ballistic missile could be increased, making its range similar to the ARRW's.

Other weapons that CBO included in its comparison, such as subsonic cruise missiles (like the Navy's Tomahawk), have ranges longer than the air-launched hypersonic boost-glide missile (ARRW) but shorter than the ground- or sea-launched hypersonic boost-glide missiles (LRHW/IR-CPS). However, because those other weapons would be slower, their flight times would be much longer than the flight times of hypersonic missiles.

The U.S. military's interest in relatively long range weapons is driven by an assumption that the defensive systems in Chinese and Russian A2/AD areas would be effective. Those defensive systems require sophisticated intelligence collection and broad surveillance, which is almost certainly not constant or complete. Without detailed information about the tracking and targeting capabilities of Chinese and Russian air-defense and antiship systems, the severity of those A2/AD threats cannot be definitively determined.

Responsiveness

One of the main reasons that DoD is developing hypersonic missiles is that they can reach their targets very quickly from relatively long distances—a capability that is lacking in the current U.S. arsenal of longer-range conventional weapons. Quick response times also require

that missiles' launchers already be located within range of their targets.

The U.S. arsenal currently lacks medium- and intermediate-range ballistic missiles primarily because the Intermediate-Range Nuclear Forces (INF) treaty between the United States and the Soviet Union prohibited either country from developing or possessing ground-launched missiles with ranges between 500 km and 5,500 km. The treaty did not limit air- or sea-launched missiles of those ranges, but the United States did not develop such ballistic missiles, presumably because they were considered too inaccurate and expensive to function as conventional weapons and were not considered necessary for nuclear deterrence.

One reason that DoD initially became interested in developing hypersonic boost-glide missiles is that their flight path (which involves spending less than half their flight in a ballistic trajectory) would make them compliant with the terms of the INF treaty. However, the United States withdrew from the treaty in 2019, citing Russian violations. That withdrawal widens the range of possible solutions to the problem of Russia's and China's efforts to develop longer-range weapons that increase the distance at which U.S. forces might have to operate. The U.S. military has chosen to continue to focus on developing hypersonic weapons to meet its desire for fast medium- and intermediate-range missiles, rather than focusing on simpler alternatives, such as ballistic missiles with maneuverable reentry vehicles.

Estimating Average Speeds of Missiles

To measure the responsiveness of hypersonic missiles and other weapon systems, CBO estimated their flight times, taking into account such factors as range, initial speed, propulsion, trajectory, and loss of speed during flight because of drag. Different types of missiles have very different flight profiles, which can make comparing flight times difficult. For example, a cruise missile flies at a constant speed throughout most of its trajectory; a hypersonic boost-glide missile accelerates rapidly to a high speed and then slows down steadily as it glides along its trajectory; and a ballistic missile accelerates rapidly, slows for the first half of its trajectory, and then accelerates again for the second half of its trajectory.

To facilitate comparison, CBO calculated a missile's average speed for each range, defined as the distance along the Earth's surface between the launcher and the target

Table 3-2.

Average Speeds of Selected Weapons at Different Ranges

Range (Kilometers)	Ballistic Missile		Hypersonic Boost-Glide Missile	Hypersonic Cruise Missile	Long-Range Subsonic Bomber	Subsonic Cruise Missile
	Minimum-Energy Trajectory	Depressed Trajectory				
1,000	6	7–8	5–9	5–9	0.95	0.7
3,000	9	10–13	9–11	n.a.	0.85	0.7
10,000	16	18–20	9–14 ^a	n.a.	0.7	n.a.

Data source: Congressional Budget Office, using data from Albert D. Wheelon, “Free Flight of a Ballistic Missile,” *American Rocket Society Journal*, vol. 29, no. 12 (December 1959), pp. 915–926, <https://doi.org/10.2514/8.4944>; Lisbeth Gronlund and David C. Wright, “Depressed Trajectory SLBMs: A Technical Evaluation and Arms Control Possibilities,” *Science & Global Security*, vol. 3, no. 1–2 (1992), pp. 101–159, <https://tinyurl.com/2p8jnb48>; James M. Acton, “Hypersonic Boost-Glide Weapons,” *Science & Global Security*, vol. 23, no. 3 (2015), pp. 191–219, <https://tinyurl.com/yc79ph7x>; and Cameron L. Tracy and David Wright, “Modelling the Performance of Hypersonic Boost-Glide Missiles,” *Science & Global Security*, vol. 28, no. 3 (2020), pp. 135–170, <https://tinyurl.com/3upn3pk2>. See www.cbo.gov/publication/58255#data.

Average speed is calculated with respect to the ground—that is, velocity equals range divided by flight time. Where the table shows a range of average speeds, the lower number reflects conservative estimates of a weapon’s trajectory and design considerations, and the higher number reflects optimistic estimates of trajectory and design considerations. “Mach number” refers to an object’s speed relative to the speed of sound in the air at sea level; for example, Mach 5 is five times the speed of sound.

n.a. = not applicable.

a. CBO concluded that with current technology, hypersonic boost-glide weapons are unlikely to be able to reach a range of 10,000 kilometers because of heating. However, estimates for that range are included for purposes of comparison.

divided by the missile’s time in flight (see Table 3-2). Although most of the missiles in CBO’s comparison have ranges of 3,000 km or less, CBO analyzed weapons with ranges between 500 km and 10,000 km (about 300 miles to 6,200 miles) for completeness.

In its current development programs, DoD is designing hypersonic boost-glide missiles with likely ranges between 1,000 km and 3,000 km (about 600 miles to 1,900 miles). To estimate the flight time of such missiles, CBO created a model of a boost-glide trajectory that was based on an evaluation of publicly available data from an earlier flight test and potential improvements that DoD says it has made since then, allowing the missiles to glide faster and longer inside the atmosphere without damage from heating.² The actual performance of those missiles is probably somewhere between the previously demonstrated performance and the assumed improvements that CBO included in its model. (For more details about CBO’s modeling of missiles, see Appendix B.)

For ballistic missiles, the longest flight time to a given target is the one associated with flying a

minimum-energy trajectory (the path that allows the missile to have the longest possible range). The flight time of a ballistic missile can be shortened by altering the trajectory to a lower, but still arcing, path known as a depressed trajectory. The differences in flight times between a minimum-energy trajectory and a depressed trajectory become more pronounced over longer ranges (see Figure 3-1). CBO estimates that for ballistic missiles traveling 1,000 km to 3,000 km, depressed trajectories reduce flight times by 10 percent to 30 percent compared with minimum-energy trajectories.³

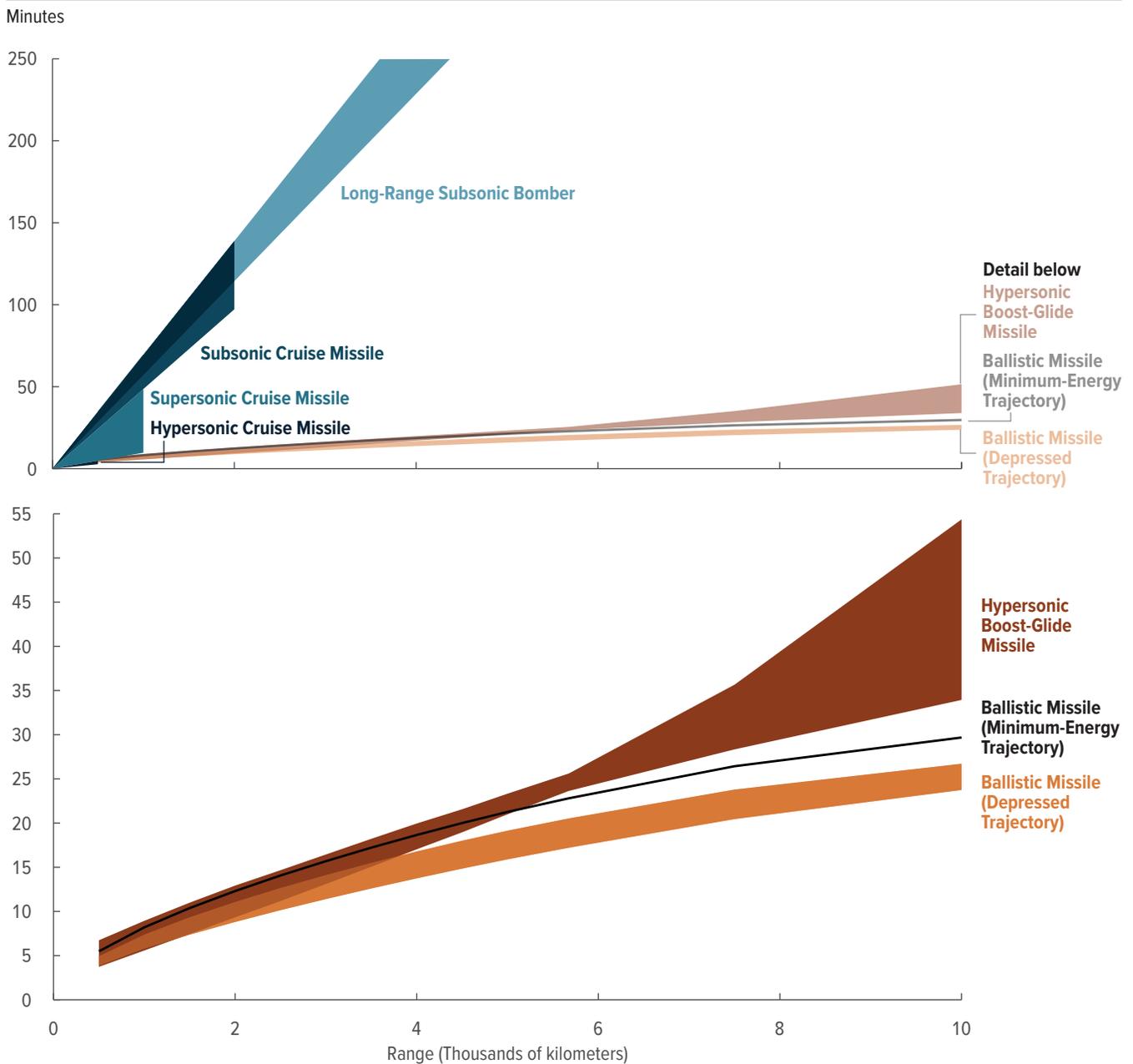
A ballistic missile on a depressed trajectory generally spends more time in the atmosphere than a ballistic missile on a minimum-energy trajectory. As a result, it may also face greater thermal challenges, which can limit either its speed or its maximum range. However, a ballistic missile experiences those challenges for a much smaller portion of its flight than a hypersonic boost-glide missile of the same range.

2. See James M. Acton, “Hypersonic Boost-Glide Weapons,” *Science & Global Security*, vol. 23, no. 3 (2015), pp. 191–219, <https://tinyurl.com/yc79ph7x>.

3. See Lisbeth Gronlund and David C. Wright, “Depressed Trajectory SLBMs: A Technical Evaluation and Arms Control Possibilities,” *Science & Global Security*, vol. 3, no. 1–2 (1992), pp. 101–159, <https://tinyurl.com/2p8jnb48>.

Figure 3-1.

Spans of Flight Times for Hypersonic and Other Weapon Systems



CBO modeled the flight times for various types of missiles and bombers. Ballistic and hypersonic missiles had the shortest flight times over all of the ranges in CBO’s analysis.

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

CBO modeled flight times for cruise missiles and subsonic long-range bombers using average speed along a flat trajectory. The range of flight times for those weapon systems reflects their range of speeds. For example, a supersonic cruise missile may travel 1,000 kilometers in as little as 10 minutes when flying at the fastest supersonic speed (just below Mach 5, or five times the speed of sound) or in as much as 48 minutes if flying at the slower end of the supersonic range (just above Mach 1). For ballistic missiles, CBO modeled flight times for a missile on a minimum-energy trajectory (which allows the missile to fly the longest distance) and on a range of depressed trajectories (with lower overall altitudes and modified booster properties that increase initial speeds). For hypersonic boost-glide missiles, the range of estimated flight times reflects a range of potential initial energies and trajectories that span the performance parameters suggested by current U.S. development programs.

For cruise missiles and subsonic bombers, the end of the colored band represents the estimated maximum range. CBO does not know the maximum range for hypersonic boost-glide missiles, but it extended the analysis to 10,000 kilometers to compare their potential flight times with those of ballistic missiles, which can currently achieve intercontinental ranges up to 12,000 kilometers.

Cruise missiles fly at low altitudes at roughly constant speeds. For its analysis, CBO used generic definitions of speed to group weapons into subsonic, supersonic, and hypersonic categories. On the basis of publicly available information, CBO limited the speed of the hypersonic cruise missiles currently under development to Mach 9.

In its comparison, CBO also considered long-range, subsonic stealth bombers, such as the current B-2 or the planned B-21, which could penetrate an adversary's A2/AD zone to deliver short-range guided weapons, such as the Joint Direct Attack Munition. To model that type of mission, CBO assumed the aircraft would fly at speeds between Mach 0.7 and Mach 0.85 and have a maximum range of 10,000 km.

The flight times that CBO calculated for a given distance between launcher and target would be increased if a missile or aircraft did not fly a direct route to its target. That increase could be significant for boost-glide and cruise missiles. Boost-glide missiles would suffer an additional speed penalty because they are unpowered, so they would lose energy during the maneuvers necessary to fly an indirect route to the target.

Responsiveness of Hypersonic Boost-Glide Missiles and Ballistic Missiles

Actual flight speeds for hypersonic missiles depend on many design considerations, such as their initial acceleration, aerodynamic shape (which affects drag), limits on maximum speed because of heating, and requirements for a maximum terminal speed (the speed at which the glide body approaches its target). CBO's estimates of response times take into account a range of potential design choices and improvements to drag conditions, but they do not account for any reductions in speed caused by maneuvering, which would increase flight times for hypersonic missiles. (For more information about how CBO estimated the upper and lower bounds on average speed for each type of missile, see Appendix B.)

Short Range. At ranges of less than about 1,000 km, there is significant overlap in the span of flight times for boost-glide and ballistic missiles, CBO estimates (see Figure 3-1, bottom panel). The hypersonic boost-glide missiles currently being developed by the United States are likely to have longer response times than ballistic missiles flying depressed trajectories. But if the United States can develop technologies that allow glide bodies to move faster without burning up, future boost-glide

missiles have the potential to achieve roughly the same response times at short ranges as ballistic missiles flying depressed trajectories and slightly shorter response times than ballistic missiles flying minimum-energy trajectories (METs). How significant that small time advantage would be in combat is not clear.

Intermediate Range. At ranges greater than 1,000 km, hypersonic boost-glide missiles are likely to take longer to reach their targets—even under optimistic performance assumptions—than ballistic missiles on depressed trajectories. Boost-glide missiles may still take less time than MET missiles at ranges of less than about 5,000 km, but that advantage dissipates with range.

Long Range. Beyond 5,000 km, the shortest estimated response times of hypersonic boost-glide missiles exceed those of MET missiles. At those longer ranges, the time advantage that hypersonic boost-glide missiles gain by traveling a shorter path because of their low-altitude trajectory is offset by the reduction in speed that they experience because of drag as they fly through the atmosphere.

In addition, as range increases, estimates of the time difference between hypersonic boost-glide and ballistic missiles become increasingly sensitive to the hypersonic missiles' design parameters and initial speeds.

Responsiveness of Hypersonic Cruise Missiles

Hypersonic cruise missiles, which are powered by supersonic combustion ramjets, are likely to operate at speeds between Mach 5 and Mach 9. Because of their low, flat trajectory, hypersonic cruise missiles flying at those speeds would take less time to reach their targets than either boost-glide or ballistic missiles at very short ranges. Cruise missiles can end their flight at roughly any location between launch and their maximum range. By contrast, ballistic and boost-glide missiles designed for a certain range have a minimum distance they must fly as well as a maximum range.

CBO used a simple model of the flight time of cruise missiles, which does not take into account trade-offs between the burnout speed of the booster that provides initial acceleration and the ability of the scramjet to continue that acceleration (rather than just maintain the speed achieved by the booster). Using average speeds that do not depend on those design choices, CBO concluded that hypersonic cruise missiles would lose their

time advantage over ballistic missiles between ranges of 700 km and 800 km.

Although scramjet technology has been demonstrated in both ground tests and flight tests, it would still require significant development to be able to be integrated into a useful weapon. DoD has stated that scramjet technology will allow for smaller, lighter cruise missiles that can be loaded on short-range tactical aircraft. Keeping the missiles' mass small enough, however, would require making concessions on both speed and range. Given those challenges, CBO limited the range for first-generation hypersonic cruise missiles in its analysis to about 500 km. The size of those missiles would limit the types of aircraft that could carry them and the number of missiles that would fit on an aircraft.

Responsiveness of Subsonic and Supersonic Cruise Missiles and Subsonic Bombers

Subsonic cruise missiles, such as the Navy's Tomahawk, are considerably slower than hypersonic missiles and ballistic missiles of the same range, flying at an average speed of Mach 0.7, CBO estimates. CBO compared subsonic cruise missiles with speeds up to Mach 1 over the ranges available with existing weapons—up to about 2,000 km—and found that their flight times would be 9 to 11 times as long, on average, as those of hypersonic boost-glide missiles and ballistic missiles of the same range (see Figure 3-1 on page 28, top panel).

Supersonic cruise missiles would have flight times between those of subsonic and hypersonic cruise missiles. DoD does not currently field such weapons, nor is it developing them. But CBO included hypothetical supersonic cruise missiles in its analysis for comparison.

An Air Force B-2 bomber can fly at a maximum speed of Mach 0.95, offering similar response times but longer ranges than a subsonic cruise missile. The bomber's flight path, however, can increase or decrease the total response time for a strike, depending on the bomber's initial location and on whether it or its missile has to take a more circuitous path than the cruise missile to avoid defenses.

Importance of Positioning

The time needed to prepare a missile for launch includes positioning the launcher (whether it is located on land, at sea, or on an aircraft) so its weapons will be within range of the target. In a scenario in which the United States did not have time to move ships, submarines, and

aircraft into position, ground-based launchers kept in the region would probably be able to launch missiles the most quickly and therefore be the most responsive. In scenarios in which the United States had more time to build up its forces in the region, it might be able to launch missiles from other platforms relatively quickly if they were in position.

Survivability

For a missile to be effective at destroying its target, its launcher must survive any attacks before launching the missile. And once launched, the missile must survive any attempts by air defenses or missile defenses to intercept it before it reaches its target.

Survivability of Launchers

The easiest way for a launcher to survive is to remain out of range of weapon systems that can attack it. Those systems include land-attack cruise missiles, ballistic missiles, and bombers for attacking ground-based launchers; antiship cruise and ballistic missiles and antisubmarine forces for attacking sea-based launchers; and air defenses and fighter aircraft for attacking airborne launchers. The need to avoid such weapon systems puts a premium on longer ranges for U.S. missiles.

Launchers that must operate within an antiaccess and area-denial zone can use several strategies to increase their chances of survival:

- They can operate near the outer edges of the A2/AD zone, which boosts survival because adversaries typically have fewer weapon systems with long ranges and fewer sensors that can detect launches at those ranges. In general, the risk of attack tends to rise the closer a launch platform is to the adversary's territory.
- They can move so they are harder to track and hit.
- They can use stealth characteristics (as submarines and stealth bombers do) or camouflage (as ground-based launchers hidden among trees do) to avoid being detected. That ability means submarines are more likely to survive than surface ships, and stealth aircraft are more likely to survive than their nonstealth counterparts.
- They can be protected by active defenses, such as missile and air defenses.

There are limits to how long a launcher of shorter-range missiles can use those strategies to survive within an

A2/AD zone. For example, stealth aircraft become more vulnerable if they must loiter in range of air defenses. The same is true for ships moving at sea. But if those aircraft or ships must remain outside the A2/AD zone for protection until the last possible moment, the promptness of their missile strikes will be delayed by the extra time it takes them to get into position (within the range of the missiles they carry).

Survivability of Missiles

Once launched, strike missiles must survive any defenses that adversaries have deployed before they can hit their targets. One of the most advertised features of hypersonic missiles is their ability to penetrate defenses. The trajectories flown by hypersonic boost-glide and cruise missiles have inherent advantages for survival, but they also have unique vulnerabilities.

In general, strike missiles are difficult to defend against. Some (such as subsonic cruise missiles) fly low, staying below the horizon for much of their flight so they cannot be detected by radar until they are close to their targets.⁴ Others (such as ballistic missiles and supersonic cruise missiles) use speed to reduce the effectiveness of defenses. Some missiles can also maneuver to make it harder for a defender to target or intercept them, and some can use countermeasures to help them penetrate defenses. For example, ballistic missiles can deploy decoys outside the atmosphere to make it more difficult for a defender to find and track the real warheads.

Hypersonic missiles are designed to use speed, altitude, and maneuvering to penetrate defenses. They fly almost as fast as ballistic missiles, but at lower altitudes. They also have the potential to maneuver midflight, either in altitude or in direction. Those features make it harder for them to be detected, tracked, and intercepted by air defenses (because they are too high to reach and too fast to catch) or by missile defenses (because they are too low to detect until late, too low for many midcourse interceptors to hit, and in many cases too maneuverable to track and intercept effectively with current interceptors). China and Russia are developing hypersonic weapons for just those reasons. They see advantages in having short- and medium-range missiles that could penetrate the missile defenses that protect U.S. forces (particularly ships) in a theater of operations, as well as advantages

in having long-range missiles that could penetrate the missile defenses that provide some protection for U.S. territory.

At the same time, the extreme heat that hypersonic missiles generate in the atmosphere makes them likely to be detectable by infrared sensors; the United States is developing space-based infrared sensors for that purpose. In addition, the trajectory of hypersonic boost-glide missiles near the end of flight is similar enough to that of aircraft that they may be vulnerable to air defenses. The effectiveness of air defenses would depend on the relative speeds and maneuverability of the interceptor and of the hypersonic missile near the end of its flight, when it had slowed considerably.

Benefits of Flying at Lower Altitudes. To illustrate the effects of geometry on the ability of a radar to detect a missile, CBO calculated the radar horizon distance, or the distance at which an object at a given height can be physically seen by a radar. Because the Earth is spherical, a radar cannot see objects that are below the horizon. Thus, a missile will remain out of view of a radar as long as it is below the radar's horizon (see Figure 3-2). Missiles can be detected earlier in their flight if the radar's altitude is increased—say, by giving the radar a taller antenna or putting it on an aircraft.

The first opportunity to detect a ballistic or hypersonic missile is during the boost phase, when its rocket motors emit a great deal of heat (infrared energy). Boost-phase detection systems are usually based in space, where factors such as the horizon are less relevant. The United States and the Soviet Union both initially deployed space-based infrared systems during the Cold War to detect long-range ballistic missile attacks by one another. U.S. infrared systems have also proved useful for detecting launches of shorter-range ballistic missiles. Although those systems were developed for ballistic missiles, they would apply equally well to detecting launches of hypersonic boost-glide missiles, because both types of missiles get their initial boost from similar large rocket motors. (The boost phase is short, lasting just a few minutes, but an initial track of a ballistic missile can usually be calculated before the boosters burn out.) Current space-based systems have limited ability to detect launches of cruise missiles.

CBO's calculations indicate that a hypersonic boost-glide missile can avoid being detected by ground-based radar

4. See Congressional Budget Office, *National Cruise Missile Defense: Issues and Alternatives* (February 2021), www.cbo.gov/publication/56950.

Figure 3-2.

Effects of Altitude on a Radar's Ability to Detect a Missile



Because of the curvature of the Earth, a radar cannot detect a missile that is below the horizon. The distance to a radar's horizon increases with the height of the radar's antenna and the altitude of its target.

Data source: Congressional Budget Office.

Radars' actual horizon limits are much shorter than they appear in this figure because the figure is not to scale.

located near the target for much more of its flight than can a ballistic missile on a minimum-energy trajectory, particularly as ranges increase. For example, if a radar's antenna was 30 meters above the ground, it would detect a notional hypersonic boost-glide missile with a range of 1,000 km when the missile was just over 40 km above the Earth, about 850 km away from the radar (see Figure 3-3, left panel). A ballistic missile on a MET would be detectable only a little bit earlier.

On a longer flight, however, the relative advantage of the hypersonic boost-glide missile's lower altitude is much greater. For instance, if the missile was traveling 3,000 km, it would not be detectable when it reached its apogee (highest point), and thereafter it would continue to spend most of its flight below the radar's horizon. Like the shorter-range boost-glide missile, it would come into continuous view about 850 km away from the radar, when it was gliding at an altitude of about 40 km (see Figure 3-3, right panel). The ballistic missile on a minimum-energy trajectory, by comparison, could be

detected on its initial ascent and would remain in view of the radar for the remainder of its flight (assuming the radar was powerful enough to detect missiles 3,000 km away). A ballistic missile on a depressed trajectory would be visible for less time than one on a MET, but it would still be detectable for the majority of its flight.

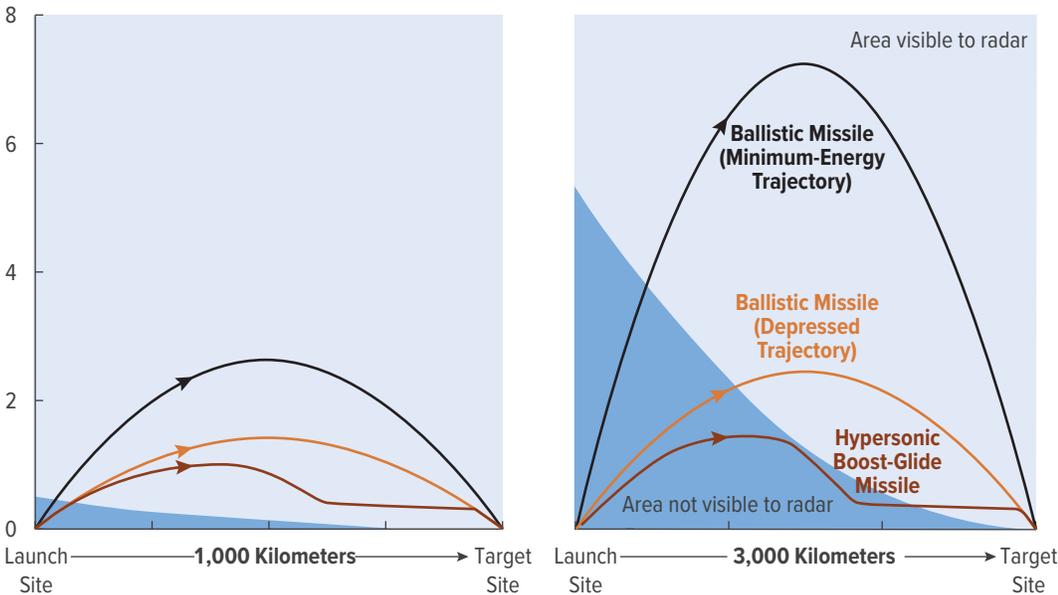
The ability to detect and track a missile at any point does not automatically translate into the ability to intercept it. Effective defenses in the correct position are needed for that. Neither China nor Russia has yet deployed defenses that are likely to be very effective against medium- or intermediate-range ballistic missiles in the middle of their flight. But if those countries did, hypersonic missiles have features that would be advantageous against midcourse-phase missile defenses.

A missile defense system's interceptors must be designed to operate either inside the atmosphere (using control surfaces to maneuver and materials and sensors that can tolerate atmospheric heating) or outside the atmosphere

Figure 3-3.

Points at Which Hypersonic and Ballistic Missiles Could Be Visible to Ground-Based Radar at Ranges of 1,000 Kilometers and 3,000 Kilometers

Altitude (Hundreds of kilometers)



Because of its altitude, a ballistic missile would theoretically be visible to a radar located at the target site much earlier in its flight than a hypersonic boost-glide missile would be. To detect and track a missile, however, the radar would have to be powerful enough to generate a signal that would reach the missile.

Data source: Congressional Budget Office.

In this example, the radar is located next to the target and has an antenna 30 meters high.

Ballistic missiles' trajectories are roughly parabolic, whether a missile is flying a minimum-energy trajectory (which allows it to fly the longest distance) or a depressed trajectory (with lower overall altitudes and modified booster properties that increase initial speeds). The trajectory of a boost-glide missile is modeled as a ballistic flight for the first half of its range, followed by a rapid descent to the glide altitude and a slowly descending glide path for the second half of its range.

In CBO's modeling, visibility to radar is a simple geometric calculation based on the curvature of the Earth, the altitude of the missile, the distance to the target, and the refraction of the radar caused by the atmosphere. That calculation indicates only that the missile could be visible above the horizon; the radar would need to have enough power and resolution to actually detect the missile.

(using thrusters to maneuver). Missile defenses that are designed to intercept ballistic missiles when they are outside the atmosphere in the midcourse phase of their flight cannot be used to intercept missiles inside the atmosphere, such as hypersonic boost-glide missiles during their glide phase.

Benefits of Flying Unpredictable Trajectories. The predictable path of a ballistic missile can be tracked with relative ease without continuous observation. Midcourse ballistic missile defense systems, such as the U.S. Ground-Based Midcourse Defense, rely on a combination of satellites to detect a launch, terrestrial radar and physics calculations to track the missile, and interceptors that are designed to engage the missile's warhead during the midcourse phase of its flight using the system's

prediction of where the missile will be when the interceptor reaches it.

Hypersonic missiles pose challenges for such midcourse defense systems because they have the potential to make unpredictable changes to their flight path. That maneuverability has two implications for midcourse defenses. It requires that a hypersonic missile be tracked along much of its flight path. And it requires either that interceptors be located close enough to reach the hypersonic missile and intercept it before it maneuvers again or that the interceptors have enough energy to respond to a maneuver and still be able to reach the missile in time to intercept it.

Hypersonic boost-glide missiles fly on a coasting trajectory from an initial height in the atmosphere. To achieve

that glide trajectory, the missile must be able to divert from its initial ballistic trajectory at some point, reenter the atmosphere, pull up, and start gliding. Near the end of the flight, it must also be able to initiate a rapid descent from its glide height. Designers hope to develop hypersonic glide bodies that can maneuver evasively, either as a response to detection or attempted engagement, or as a way to introduce uncertainty about their trajectory and ultimate target by executing a preset series of maneuvers unknown to the adversary. (Those maneuvers would reduce the speed of the missile, however, increasing its flight time and shortening its range.)

Responsive maneuvering is much harder to achieve than preplanned evasive maneuvering, but both are significant challenges for an object traveling through the atmosphere at hypersonic speeds. The Army, Navy, and Air Force are not pursuing responsive maneuvering in their boost-glide missile programs, but some research programs are looking into that technology.

Net Effect on Survivability. For all of the reasons noted above, hypersonic boost-glide missiles are likely to be detected on launch, but current defensive systems lack the ability to reliably intercept them. In the midcourse phase, acquiring tracking data with sufficient resolution to target the missiles with interceptors will be difficult unless potential adversaries develop space-based infrared sensors to track boost-glide missiles by their heat. Developing interceptors with enough agility and maneuverability to engage those missiles will also be difficult. Intercepting missiles in the midcourse phase is challenging, even with good tracking data and even for ballistic missiles (because they can employ countermeasures). The difficulty would be greater in some respects with hypersonic missiles, but the end effect might not be different, because neither China nor Russia can intercept long-range ballistic missiles today.

Terminal-phase defense systems may be better suited to intercepting hypersonic missiles, because the missiles will be close enough to track with ground-based radar and will be traveling at lower speeds by that time (possibly below Mach 5, in the supersonic range). However, terminal defenses have not been designed to counter hypersonic missiles. In addition, they are generally intended to cover a relatively small area, which makes them more appropriate for protecting high-value targets against attack than for protecting large portions of a country.

It is unclear how much advantage hypersonic missiles would have over ballistic missiles with maneuverable

warheads against shorter-range, terminal defenses. By flying low, hypersonic missiles could force the ground-based radar associated with short-range defenses to detect a missile later in flight, shortening the time the defense has to intercept it. But because hypersonic missiles use up much of their energy during their glide, they are likely to be traveling more slowly than MaRVs as they near their targets. And both types of missiles can perform preprogrammed maneuvers near their targets to complicate the task of intercepting them.

Overall Effectiveness in an Antiaccess and Area-Denial Environment

The combination of range, responsiveness, and survivability determines the overall effectiveness of a weapon in an antiaccess and area-denial environment. Effectiveness is defined here as the ability to strike targets of interest given the constraints on distance, basing, and time imposed by an A2/AD environment and by U.S. strategy.

Trade-Offs Between Weapons' Characteristics

Significant trade-offs exist between range, speed, and platform survivability. Many existing weapon systems perform extremely well by some of those measures, but they do not combine all of the features needed to be effective in an A2/AD zone, particularly during the early stages of a conflict. For example, Tomahawk cruise missiles have only a medium range (approximately 2,000 km), but they can potentially be launched from submarines operating well inside A2/AD defenses. Because they fly at very low altitudes and can follow routes that avoid known defenses, they would be survivable on the way to their targets, but they might be vulnerable if there were sophisticated defenses around the targets. Tomahawk missiles are slow and could take up to two hours to reach their targets, depending on the location of the submarines from which they were launched. If submarines could not operate close to the target, faster missiles with longer range would be needed to provide short response times.

The specific capabilities of an adversary's defenses are also important. For example, an opponent might have sensors that could detect and track a high-flying strike missile but might lack weapons that could shoot down the missile. (Early detection might still be useful if it allowed people in the target area to be alerted in time to take cover or otherwise prepare for an attack.) Conversely, a surface-to-air missile system with long-range interceptors might not be able to take advantage of its interceptors'

Table 3-3.

Range That a Missile Can Travel in 15 Minutes at Various Average Speeds

Average Speed (Mach number) ^a	Range in 15 Minutes (Kilometers)	Missiles That Can Travel at That Average Speed	Defensive A2/AD Systems in That Range
0.7	200	Subsonic cruise missiles	Surface-to-air missiles
1	300	Supersonic cruise missiles	Surface-to-air missiles
5	1,500	Hypersonic cruise missiles, medium-range ballistic missiles	Fighter aircraft
10	3,000	Hypersonic boost-glide missiles, intermediate-range ballistic missiles	Air-launched cruise missiles
15	4,500	Intermediate-range ballistic missiles	Antiship ballistic missiles

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

The distance that the missiles could travel in 30 minutes would be roughly twice the ranges shown here.

A2/AD = antiaccess and area-denial.

a. "Mach number" refers to an object's speed relative to the speed of sound in the air at sea level; for example, Mach 5 is five times the speed of sound.

range if it could not detect a stealthy, low-flying cruise missile until the missile was very close. Likewise, China's long-range antiship missiles would only be effective if paired with the ability to detect and track ships at similarly long ranges.

An arsenal that included a variety of strike weapons with different ranges, speeds, launch modes, and flight trajectories would probably be the most successful against an adversary with defensive systems of varying capabilities.

Comparing Flight Distances Within Time Limits

A2/AD environments impose two important constraints: They increase the range at which U.S. forces would have to operate (known as the standoff distance), and that greater distance in turn lengthens the time it would take for a weapon to reach its target. U.S. doctrine for conventional warfare emphasizes striking early in a conflict and attacking some targets quickly enough that they do not have time to operate or respond effectively to the U.S. attack. Together, those factors place a premium on having very fast weapons that can operate from ranges as long as 3,000 km to 5,000 km in the case of surface-launched weapons and more than 1,000 km in the case of air-launched weapons.

CBO compared hypersonic missiles and other weapon systems by evaluating the distance that each can fly within two time constraints, 15 minutes and 30 minutes, by using the average speed over the entire trajectory. CBO's analysis indicated that two aspects of time-sensitive targeting are important, regardless of

weapon type. First, average speeds of at least Mach 5 are essential for quick strikes against all but the closest targets. Second, as the time constraint is shortened, even the highest speeds are not adequate at longer distances; proximity to the target becomes important as well.

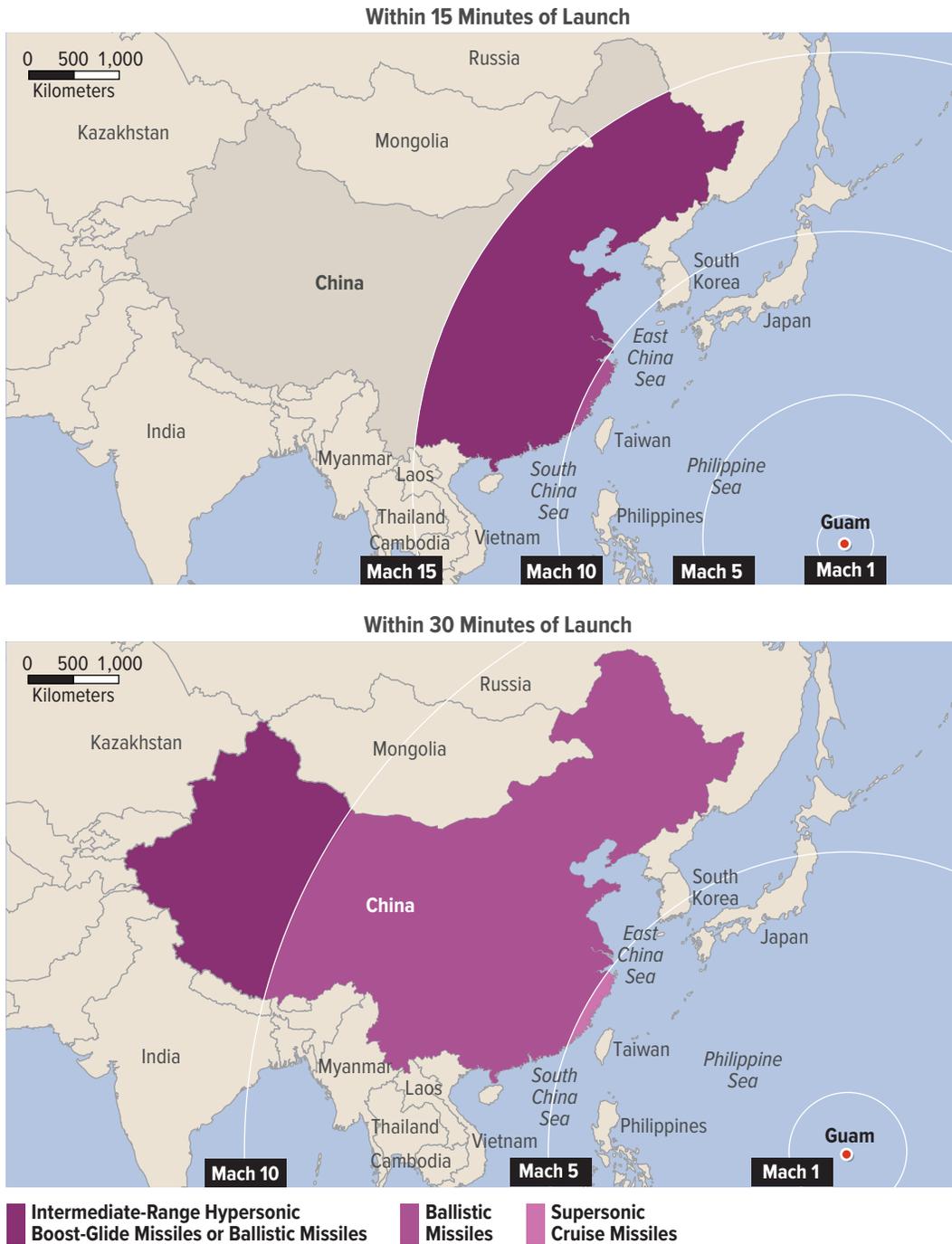
To evaluate the combined effects of standoff distance and speed, CBO calculated how far specific weapons might be able to travel in 15 minutes (see Table 3-3) and what those flight distances would mean in specific A2/AD scenarios. For example, in a South China Sea scenario, a subsonic cruise missile launched from Guam, flying at a speed slower than Mach 1, would travel roughly 200 km in 15 minutes, less than 10 percent of the way to China. A ballistic missile with an average speed of Mach 5 could travel about halfway to China (1,500 km) in that time (see Figure 3-4). Both of those ranges are too short to reach any targets of interest from Guam. A hypersonic boost-glide missile with an average speed of Mach 10 could just reach the coast of China (about 3,000 km) in 15 minutes, as could a ballistic missile with the same average speed.

In 30 minutes, higher-speed missiles (Mach 10 and above) could reach nearly all of China if they could sustain such speeds over very long ranges. That would be unlikely, however, for any type of missile other than ballistic missiles with intercontinental ranges.

In a Russia scenario focused on the Baltic region, conditions would be different because of the very different geography of that area. The shorter distances than in the

Figure 3-4.

Areas of China That a Missile Launched From Guam Could Reach Within 15 Minutes and 30 Minutes, by Average Speed



A hypersonic boost-glide missile or intermediate-range ballistic missile launched from Guam that traveled at an average speed of Mach 10 could reach the eastern coast of China in 15 minutes.

Data source: Congressional Budget Office.

The areas shown within the white circles represent the distance that a missile launched from the Pacific island of Guam and moving at an average speed of Mach 1, 5, 10, or 15 would travel in 15 minutes or 30 minutes. ("Mach" refers to an object's speed relative to the speed of sound in the air at sea level; for example, Mach 5 is five times the speed of sound.) The speed regimes correlate to subsonic cruise missiles (lower than Mach 1), supersonic cruise missiles (between Mach 1 and Mach 5), hypersonic cruise missiles (between Mach 5 and Mach 9), and hypersonic boost-glide missiles (average speeds between Mach 10 and Mach 15). Ballistic missiles could be designed with average speeds between Mach 5 (shorter range) and Mach 15 (longer range). Despite their speed, hypersonic cruise missiles would not be able to reach China from Guam, because their range will be limited to 1,000 kilometers or less by the amount of fuel they can carry.

Pacific suggest that shorter-range weapons could play a greater role early in a conflict, particularly if U.S. forces were stationed east of Germany. For example, a missile launched from the Germany–Poland border that had an average speed of Mach 5 could reach all of the Baltic Sea nations and into Russia in 15 minutes (see Figure 3-5). A missile averaging Mach 10 could reach more than 2,000 km into Russia in that time. The same missiles based in Poland or Finland (which has applied to join NATO) could reach even farther into Russia.

In the Baltic scenario, missiles launched from ships or submarines would probably play a smaller role than missiles launched from aircraft or ground-based launchers. U.S. and allied forces would mostly be operating from land or in the air because Russia’s antiship missiles could limit naval access to the Baltic Sea. The addition of Finland to NATO would also reduce the need for sea-launched options. Ground forces might play a particularly prominent role in that scenario because they are more difficult to detect and destroy than aircraft or ships.

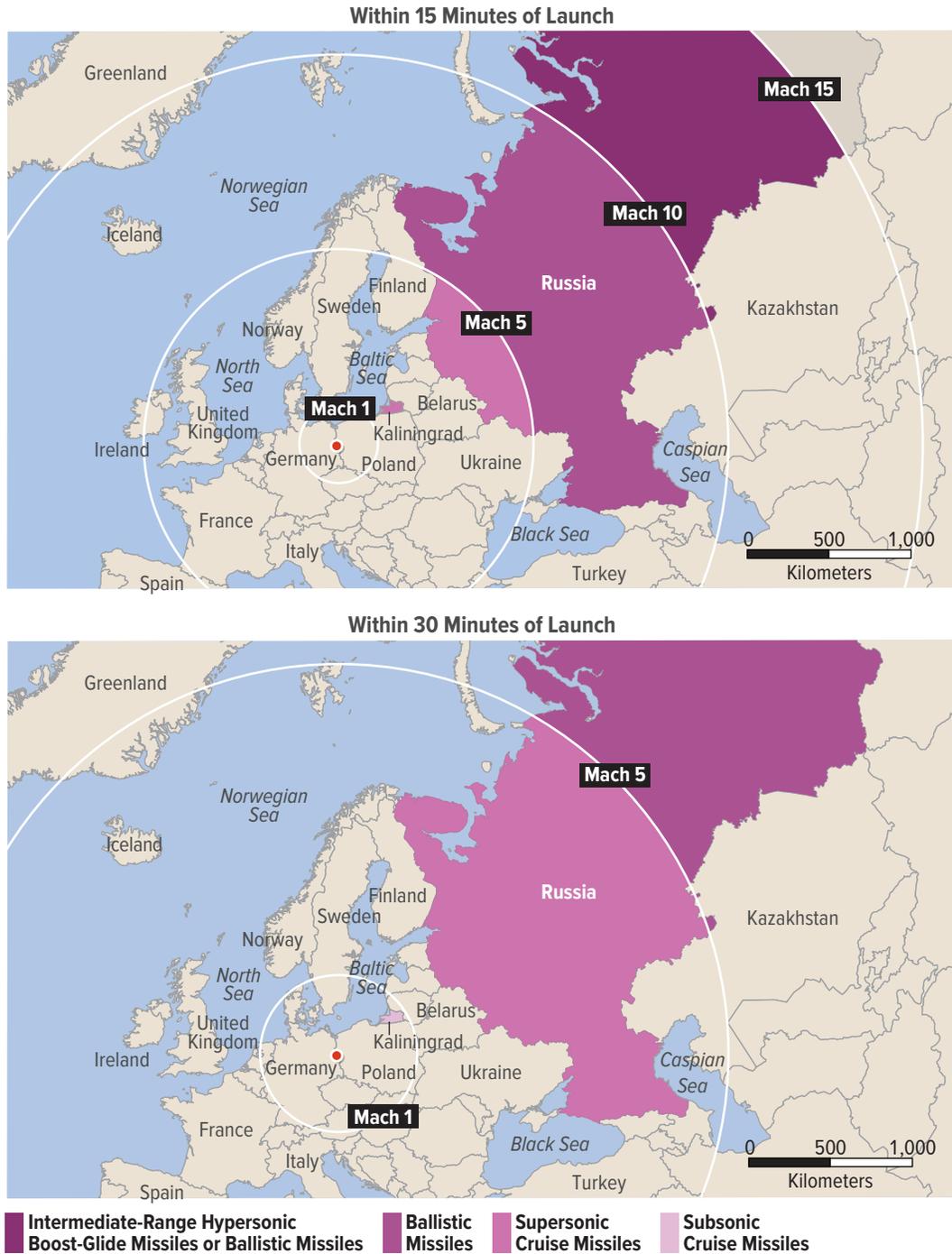
Maturity of Weapon Systems

The analyses described in this chapter compared weapon systems as though they were all technologically mature enough for deployment. But as another point of comparison, CBO also assessed the current development status of those systems (see Table 3-4).

Of the weapon systems in CBO’s analysis, only intercontinental ballistic missiles and subsonic cruise missiles exist today in the U.S. inventory. Hypersonic boost-glide missiles and hypersonic cruise missiles are under development in the United States. But creating effective versions of those missiles is likely to pose greater technological challenges than would developing supersonic cruise missiles (which have been demonstrated by other countries) or medium- to intermediate-range ballistic missiles with MaRVs (which were part of the U.S. arsenal before the INF treaty and have some components, such as rocket boosters, roughly equivalent to those of hypersonic missiles).

Figure 3-5.

Areas of Russia That a Missile Launched From Germany Could Reach Within 15 Minutes and 30 Minutes, by Average Speed



A hypersonic boost-glide missile or intermediate-range ballistic missile launched from the border of Germany and Poland that traveled at an average speed of Mach 10 could reach about 1,800 kilometers into Russia in 15 minutes.

Data source: Congressional Budget Office.

The areas shown within the white circles represent the distance that a missile launched from the eastern border of Germany and moving at an average speed of Mach 1, 5, 10, or 15 would travel in 15 minutes or 30 minutes. ("Mach" refers to an object's speed relative to the speed of sound in the air at sea level; for example, Mach 5 is five times the speed of sound.) The speed regimes correlate to subsonic cruise missiles (lower than Mach 1), supersonic cruise missiles (between Mach 1 and Mach 5), hypersonic cruise missiles (between Mach 5 and Mach 9), and hypersonic boost-glide missiles (average speeds between Mach 10 and Mach 15). Ballistic missiles could be designed with average speeds between Mach 5 (shorter range) and Mach 15 (longer range). Despite their speed, hypersonic cruise missiles would not be able to reach deep into mainland Russia from Germany, because their range will be limited to 1,000 kilometers or less by the amount of fuel they can carry.

Table 3-4.

Characteristics of Different Missiles Included in This Analysis, by Development and Funding Status

Key:

- = Mature Technology
- ☑ = In Development as Part of DoD’s Current Budget Plan
- = Would Require Investment Not in DoD’s Current Budget Plan

Weapon Type	Exist Today in U.S. Inventory	Average Speed Greater Than Mach 5 ^b	Range Greater Than 3,000 km ^c	Accurate Enough to Use a Conventional Warhead ^d	Able to Survive Defenses ^a		
					Air Defenses	Midcourse Ballistic Missile Defenses	Terminal Ballistic Missile Defenses
Intercontinental Ballistic Missiles	■	■	■	□	■	□	□
Medium- to Intermediate-Range Ballistic Missiles		□	□	□	□	□	□
Hypersonic Boost-Glide Missiles		☑	☑	☑	□	☑	☑
Subsonic Cruise Missiles	■			■	□	■	■
Supersonic Cruise Missiles				□	□	□	□
Hypersonic Cruise Missiles		☑	Unknown	☑	□	☑	☑

Data source: Congressional Budget Office.

DoD = Department of Defense; km = kilometers.

- a. All of the weapons shown here are designed to have some capability against missile defenses, including air defenses and midcourse and terminal ballistic missile defense systems. Ballistic missiles, because of their trajectories and high speed, are survivable against air defenses. By using countermeasures, such as decoys, they could become more survivable against potential midcourse ballistic missile defenses that adversaries might develop; and with the introduction of end-stage maneuvering, their survivability against terminal defenses would be similar to that of hypersonic boost-glide missiles. Hypersonic boost-glide missiles would be survivable against each stage of ballistic missile defenses because of their lower altitudes and maneuverability, but they would require the greatest investment.
- b. "Mach" refers to an object's speed relative to the speed of sound in the air at sea level; for example, Mach 5 is five times the speed of sound.
- c. CBO used 3,000 kilometers as a cutoff in range that represents the ability to operate from outside the reach of most antiaccess and area-denial systems. The final maximum range remains unknown.
- d. To use conventional warheads—which have a much smaller blast radius than nuclear warheads and thus require more accuracy—ballistic missiles would need to be fitted with maneuverable reentry vehicles. Hypersonic boost-glide missiles would require similar capability at the end of their flight. (Ballistic missiles and hypersonic boost-glide missiles have similar speeds and ranges.)

Chapter 4: Comparing Options for Planned Hypersonic Missiles and Alternatives

Building on its general comparison of the range, responsiveness, and survivability of different kinds of weapon systems, described in Chapter 3, the Congressional Budget Office created five illustrative options with specific missiles to show the array of approaches that the U.S. military could use to strike targets quickly from long distances. Three of the options include hypersonic missiles that the Department of Defense is currently developing, and the other two include alternative missiles that incorporate more conventional technology:

- Option 1 consists of the Army's Long-Range Hypersonic Weapon and the Navy's Intermediate-Range Conventional Prompt Strike missile (LRHW/IR-CPS), which are intermediate-range hypersonic boost-glide missiles that would be launched from the ground or at sea, respectively. (For definitions of missiles' ranges and other characteristics, see Box 1-1 on page 6.)
- Option 2 consists of intermediate-range ballistic missiles with maneuverable reentry vehicles that could be launched from the ground or at sea. Those missiles do not exist in the U.S. inventory today, but the technology for both the missiles and the MaRVs is well developed. The United States fielded similar missiles in the 1980s, before signing the Intermediate-Range Nuclear Forces treaty. In addition, the rocket boosters for the ballistic missiles would be the same ones that DoD is developing for the LRHW/IR-CPS missiles in Option 1.
- Option 3 consists of the Air Force's AGM-183A Air-Launched Rapid Response Weapon (ARRW), a medium-range hypersonic boost-glide missile.
- Option 4 consists of an air-launched, short- or medium-range hypersonic cruise missile like the ones that the Air Force and the Navy are in the early stages of developing, the Hypersonic Attack Cruise Missile (HACM) and the Hypersonic Air-Launched

Offensive Antisurface Warfare (HALO) missile, respectively.

- Option 5 consists of a land-attack version of the Navy's existing Standard Missile-6, which would have extended range and speed and could be launched from the ground or at sea.

For those options, CBO estimated the costs to procure 300 missiles, integrate them with existing platforms, buy launchers and other associated equipment, and sustain the missile systems for 20 years (for more details, see Appendix C). In addition, CBO compared the effectiveness of the options and assessed how each could improve DoD's capability to rapidly strike targets from long distances, such as targets in adversaries' antiaccess and area-denial zones. For the hypersonic missiles now in development, CBO's estimates of capabilities are based on information publicly available from DoD.

CBO based its estimates of costs for the surface- and air-launched boost-glide missiles in Options 1 and 3 as closely as possible on public information about the characteristics of the LRHW/IR-CPS and ARRW missiles now in development and DoD's procurement goals for them. Although CBO refers to the missiles in those options as the LRHW/IR-CPS and ARRW for simplicity, CBO's estimates are not intended to predict the costs of the actual DoD programs, because considerable uncertainty remains about how those programs' schedules and inventory goals may evolve. Rather, CBO's options are meant to illustrate the relative costs of the high-speed missiles being developed by DoD and potential alternatives. CBO did not include in its estimates any calculation of the risks or consequences of cost and schedule growth. However, many complex technologies that have been fielded by DoD in the past have been subject to significant delays and cost overruns.

The five illustrative options are not mutually exclusive; DoD could field a mix of missile systems to use in specific situations. Therefore, CBO also analyzed the value of having redundancy in the U.S. inventory of counter-A2/AD weapons.

Comparing the options, CBO found that the intermediate-range ballistic missiles in Option 2 could provide the range, responsiveness, and most of the survivability of the LRHW/IR-CPS hypersonic boost-glide missiles in Option 1, at roughly three-quarters of the cost. CBO also found that ARRW hypersonic boost-glide missiles launched from aircraft (Option 3) would cost roughly one-third of what a similar number of LRHW/IR-CPS missiles would cost. But the ARRW missiles would have less range and would provide the same responsiveness only if aircraft were already in position to launch.

A smaller number of air-launched missiles could provide a worldwide availability similar to that of Option 1 or could complement intermediate-range missiles if an adversary's long-range air defenses could be degraded. Thus, CBO estimated costs for two quantities of ARRWs in Option 3: the same number of missiles as in Options 1 and 2 (300) and a smaller quantity (100) that represents a complementary capability to either Option 1 or Option 2.

The ground- or sea-launched SM-6 missiles in Option 5 would be the least costly alternative, but they would offer the lowest performance in terms of both speed and range. (CBO did not estimate costs for the hypersonic cruise missiles in Option 4, because they are still early in their development and little information about them is available.)

CBO's illustrative options are not intended to cover all possible missiles that could be used in the A2/AD and other scenarios described in Chapter 2. For example, the Navy's Tomahawk medium-range subsonic cruise missile, though relatively slow, is likely to remain a significant part of DoD's arsenal in any conflict. Indeed, the Army plans to procure Tomahawks in coming years and deploy them with ground launchers. In addition, the Air Force is developing a longer-range version of its own air-launched, long-range cruise missile, the AGM-158.

To be effective, all of the options would depend on a network of sensors, tracking systems, and communications

systems that would permit the type of over-the-horizon targeting envisioned by advocates of long-range standoff weapons. The response-time demands on those systems would be particularly great if DoD wanted to conduct rapid strikes on fleeting targets.

In general, such high-end sensor, tracking, and communications systems do not exist today. But DoD is developing a number of systems that could fulfill those roles if they proved successful. They include command-and-control systems such as the Air Force's Advanced Battlefield Management System and DoD's Joint All-Domain Command and Control System, as well as sensors and communications networks of the type that the Space Development Agency envisions for its Proliferated Warfighter Space Architecture. For the purposes of this analysis, CBO assumed that those systems had been deployed successfully, as had the aircraft and submarines that might carry the missiles in the options. However, the costs of those systems, which could be significant, are not included in CBO's analysis.

Characteristics of the Missile Options

The five notional missile systems that CBO analyzed run the gamut from intermediate- to short-range weapons and use all three launch modes (ground, sea, and air). The options vary in the state of their development and technological maturity. Two of the options feature the first-generation hypersonic boost-glide missiles that the Army, Navy, and Air Force are developing and hope to deploy in the next several years. Two other options feature hypersonic cruise missiles that the Air Force and Navy are in the early stages of designing and short-range ballistic missiles that the Navy is developing by upgrading existing missiles. The remaining option features intermediate-range ballistic missiles that are not deployed or in development but that would incorporate well-established technology that has been used in past U.S. missiles.

Option 1: Intermediate-Range, Ground- or Sea-Launched Hypersonic Boost-Glide Missiles (Similar to LRHW/IR-CPS)

Under Option 1, the Army and Navy would complete and field the hypersonic boost-glide missile they are collaborating on, the LRHW and IR-CPS, which is expected to have a range of at least 3,000 kilometers (about 1,900 miles). The missile could be launched from vehicles on land as well as from ships and submarines at sea. It would use a two-stage rocket booster to reach an

initial speed in the high hypersonic regime (Mach 15 or above), which would be necessary for it to glide to an intermediate range. The missile would reach an apogee of roughly 120 km before it reentered the atmosphere, after which the glide body would spend most of its flight at an altitude between 30 km and 40 km. The glide body would require thermal shielding to protect it and its sensitive electronics from temperatures exceeding 1,800 Kelvin (2,780° Fahrenheit).

The glide body would be enabled with the Global Positioning System, allowing the same sort of accurate and precise targeting as a Joint Direct Attack Munition guided bomb. But it would not have an onboard sensor to home in on its target during the final stage of flight. (Research to develop such a capability is ongoing, but it will not exist in the first-generation hypersonic missiles that DoD is building today.) The missile would also have a limited ability to maneuver outside of a preset course.

Missiles Deployed on Land. As reported by the Army, a hypersonic missile battery will include four transporter-erector-launchers that carry two missiles each. Reports have indicated that the Army plans to field six batteries and purchase 66 LRHW missiles. Potential launch locations in the Pacific region include the islands of Guam and Palau (and possibly countries closer to China if they were to allow the deployments). European locations could include U.S. military bases in Germany as well as bases of Eastern European and Nordic countries.

The Army's hypersonic missile units would be mobile, meaning that the exact location and time to set up and execute a missile launch might depend on the details of a particular conflict (as with an air or sea launch). However, given the time pressures in a crisis, the time between receiving target coordinates and firing a missile would probably be relatively short for a ground-based system, provided that the system had already been deployed in the theater and was ready for launch. In such circumstances, ground launch could be faster than launches from sea or air if ships and aircraft were not in position to fire immediately.

Missiles Deployed at Sea. The Navy has indicated that it plans to buy 240 IR-CPS boost-glide missiles. They would be carried on Zumwalt class destroyers and on Virginia class submarines equipped with Virginia payload module (VPM) missile tubes. Current plans call

for both Zumwalt destroyers and VPM-equipped submarines to have a maximum capacity of 12 IR-CPS missiles apiece, although it is likely that some of the missile tubes would be used for other weapons.

In the Pacific region, many launch locations at sea are possible. In the Baltic region, sea launch would probably be less likely, for two reasons: striking inland targets would be hard if Russian antiship and antisubmarine weapons limited U.S. operations in the Baltic Sea, and many alternative launch locations would be available on land. In either regional scenario, positioning a submarine or ship in an appropriate spot for launch might take significant time (hours or days). That time constraint might not be a problem in a slowly unfolding crisis, but it would create more difficulty in a sudden conflict. The coverage that a given IR-CPS missile would achieve would depend on its proximity to shore when it was launched.

For ease of comparison among the options, CBO estimated costs for a notional purchase of 300 missiles in each option. That amount is close to DoD's reported plan to purchase a total of 306 LRHW/IR-CPS missiles (66 LRHWs for the Army and 240 IR-CPSs for the Navy).

Option 2: Intermediate-Range, Ground- or Sea-Launched Ballistic Missiles Equipped With MaRVs

Under Option 2, DoD would develop and field a ballistic missile with a range of 3,000 km to 5,500 km (about 1,900 miles to 3,400 miles). The U.S. military fielded a medium-range ballistic missile armed with nuclear warheads (the Pershing II) until the late 1980s, when those missiles were destroyed in adherence to the INF treaty. The ballistic missiles in this option would have longer ranges than the Pershing II missiles and would carry conventional warheads.

The new ballistic missile would use the same two-stage rocket booster as the boost-glide missile in Option 1, but instead of a hypersonic glide body, it would be equipped with a maneuverable reentry vehicle for precise targeting. The MaRV would be able to change its flight path once it had reentered the atmosphere (in the terminal stage of flight), improving its accuracy.

CBO assumed that development of the new ballistic missile could be completed with the remaining funding

planned for the corresponding ground- or sea-launched boost-glide missiles. The ballistic missile's boosters would be the same as those being developed for the LRHW/IR-CPS, and funding currently slated for the Common Hypersonic Glide Body could be used to complete past efforts to develop MaRVs. For an earlier project to arm Trident missiles with conventional warheads (the Conventional Trident Modification program), the Navy estimated that a MaRV could be developed and enter production in as little as two years.

To minimize flight time, the new missile would fly a depressed ballistic trajectory, reaching an apogee of between 300 km and 500 km. The reentry vehicle would need thermal protection similar to that of existing ballistic missile warheads, a technology that is well developed. The range of the new missile would be limited by the mass of its payload and its trajectory rather than by heating, because the missile would spend most of its flight outside the atmosphere.

Under this option, the Army would purchase 60 of the new ballistic missiles and the Navy would purchase 240, the same quantities as in Option 1.

Option 3: Medium-Range, Air-Launched Hypersonic Boost-Glide Missiles (Similar to ARRW)

Under Option 3, the Air Force would complete development of and deploy the Air-Launched Rapid Response Weapon, a hypersonic boost-glide missile with a range that CBO estimates at roughly 1,000 km (about 600 miles). That missile would have a shorter range and lower speed than the ground- and sea-launched hypersonic missiles in Option 1. It would also be smaller, enabling it to be carried on Air Force bombers and possibly on some larger fighter aircraft. CBO's analysis suggests that the missile's average speed over a 1,000-mile trajectory would be about Mach 7. Because of its smaller booster and lower intended speed and range, the ARRW would reach a lower apogee than the LRHW and IR-CPS: an altitude of perhaps 80 km to 90 km, still inside the atmosphere.

Other features of the boost-glide missile in this option, such as accuracy and maneuverability, would be similar to those of the boost-glide missiles in Option 1 and the ballistic missiles in Option 2. The ARRW currently being developed has a more complex aerodynamic design than the LRHW and IR-CPS, which indicates that it may have the potential for more complex maneuvering or

ranges longer than 1,000 km. Whether those improvements can be achieved, however, is unclear.

The Air Force is considering several aircraft to carry the ARRW, including B-52 and B-1 bombers and F-15 fighters. Other aircraft are also possible. The B-52 is expected to be able to carry two ARRW missiles under each wing and might eventually be able to carry additional missiles internally. The F-15E and F-15EX might also be able to carry one ARRW apiece on their center-line weapon station.

The Air Force has not indicated how many ARRW missiles it plans to purchase. For this analysis, CBO estimated the costs of two ARRW procurement quantities: 300 missiles, to provide a direct comparison with the 300 LRHW/IR-CPS missiles in Option 1, and 100 missiles, to reflect the fact that fewer air-launched boost-glide missiles could provide a worldwide availability similar to that of a larger number of ground- and sea-launched boost-glide missiles.

Deploying ground units and moving submarines and ships long distances can take days or weeks. So ensuring that LRHW/IR-CPS missiles were in the right place for rapid launch would require dispersing missiles among ground batteries and ships deployed around the world. In contrast, a smaller number of ARRW missiles could be stored in just a few locations, ready to be flown to where they might be needed and launched on short notice.

Option 4: Short-Range, Air-Launched Hypersonic Cruise Missiles (Similar to HACM/HALO)

Under Option 4, the Air Force would develop and build a hypersonic cruise missile, powered by a supersonic combustion ramjet engine, with a range of less than 1,000 km. The missile would be similar to the ones envisioned in the Air Force's HACM program or the Navy's HALO program, although both of those missiles are still early in the process of development.

The Air Force missile in this option would be launched from B-52 bombers and perhaps other aircraft. It would require a small rocket booster to achieve supersonic speeds, at which point the scramjet engine would begin to operate. CBO assumed that the missile would travel at a roughly constant speed, which could be as low as Mach 5 or as high as Mach 9. It would maintain an altitude of about 30 km to 40 km for the duration of its

flight, well within the atmosphere. As a result, the engine components and external housing would have to withstand significant amounts of heating.

Estimates released by DoD indicate that its air-launched hypersonic cruise missiles would be much smaller than the air-launched hypersonic boost-glide missiles in Option 3, so up to four times as many of them could be carried on a B-52. However, the cruise missiles are in a much earlier stage of development than the boost-glide missiles, with much less mature technology, so it is not yet clear how large they would be. (CBO considers DoD's size estimate optimistic because the cruise missiles would need a rocket booster, they would have to carry fuel, and their efficiency would depend on the length of the engine.) The missiles in this option would probably also have a shorter range than the missiles in the other four options that CBO analyzed.

Because little is known about the characteristics of the hypersonic cruise missiles currently in development or the details of their underlying technology, CBO did not estimate the cost of the missile system in this option.

Option 5: Short-Range, Ground- or Sea-Launched Ballistic Missiles (Similar to SM-6 Block IB)

Under Option 5, the Army and the Navy would deploy the Standard Missile-6 Block IB, which the Navy is in the process of developing. The Block IB is a variant of the Navy's existing SM-6 Block IA, a short-range, supersonic guided missile that can be used for air defense, missile defense, and antiship warfare. Reports indicate that the Army is also interested in fielding the Block IB missile.

The new missile is a significant modification of the Block IA version, with a range that may be as long as 1,000 km and an average speed in the low hypersonic regime (Mach 5 to Mach 6). That range and speed require the development of a new, larger booster as well as enhanced sensor technology. The SM-6 Block IB missile would be used for attacking surface targets and would be powered by a two-stage rocket booster. The SM-6 Block IB is not a hypersonic boost-glide missile, because it would fly a modified ballistic trajectory and would not use the air to produce lift.

To provide a direct comparison with the other options, CBO assumed that the Army and the Navy would purchase a combined total of 300 SM-6 Block IB missiles

under this option, plus ground equipment for six Army batteries. The Army's missiles could be fired from modified ground-launch vehicles. The Navy's missiles could be fired from the same large tubes on Zumwalt class destroyers and Virginia class submarines as the IR-CPS missiles in Option 1. The Block IB missiles would also be compatible with the MK 41 vertical launchers on cruisers and Arleigh Burke class destroyers, greatly increasing the number of ships that could carry them. For that reason, it is possible that more SM-6 Block IB missiles would be purchased.

Costs of the Options

For its illustrative options, CBO estimated several types of costs: the costs to purchase the missiles; the costs to integrate the missiles with existing platforms and to buy associated equipment, such as launchers; and the costs to sustain the missile systems for 20 years. (Those estimates are described in more detail in Appendix C.) CBO did not include the costs of developing the missiles in its estimates. Also, CBO could not estimate the cost of the hypersonic cruise missiles in Option 4, because their technology remains immature and the ultimate cost to procure such a missile is unclear.

The intermediate-range hypersonic boost-glide missiles in Option 1 would be the most expensive of the options that CBO estimated, costing an average of \$41 million apiece (in 2023 dollars) to procure—about 60 percent more than the intermediate-range ballistic missiles with MaRVs in Option 2, which would cost \$26 million apiece (see Table 4-1). Including 300 missiles, five batteries of ground vehicles, launchers, ship modifications, and 20 years of sustainment would bring the total cost of Option 1 to \$17.9 billion.¹ That total is about one-third more than the cost of the intermediate-range ballistic missile system in Option 2, which would total \$13.4 billion, CBO estimates.

Of the medium- or short-range missiles in the options, the ARRW hypersonic boost-glide missiles in Option 3 would be the more expensive of the two types for which CBO estimated costs. Those air-launched boost-glide missiles would have an average procurement cost of \$15 million apiece for 300 missiles and a total cost of \$5.3 billion to procure and sustain them for 20 years.

1. Although reports have indicated that the Army plans to field six LRHW batteries, the first battery has reportedly already been equipped. Thus, the estimate for Option 1 only includes the costs of equipping the other five batteries.

Table 4-1.

Costs of the Missile Options That CBO Analyzed

	Number of Missiles Purchased	Average Procurement Cost per Missile (Millions of 2023 dollars) ^a	Costs of Option (Billions of 2023 dollars)			
			Missile Procurement ^a	Platform Integration	20 Years of Sustainment	Total ^b
Intermediate-Range Missiles (Range 3,000–5,500 km)						
Option 1: Ground- or Sea-Launched Hypersonic Boost-Glide Missiles (Similar to LRHW/IR-CPS)	300	41	12.2	2.7 ^c	3.0	17.9
Option 2: Ground- or Sea-Launched Ballistic Missiles Equipped With MaRVs	300	26	7.7	2.7	3.0	13.4
Medium-Range Missiles (Range 1,000–3,000 km)						
Option 3. Air-Launched Hypersonic Boost-Glide Missiles (Similar to ARRW) ^d	300	15	4.5	0.2 ^e	0.6	5.3
	100	18	1.8	0.2 ^e	0.2	2.2
Short-Range Missiles (Range less than 1,000 km)						
Option 4: Air-Launched Hypersonic Cruise Missiles (Similar to HACM/HALO) ^f	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Option 5: Ground- or Sea-Launched Ballistic Missiles (Similar to SM-6 Block IB)	300	6	1.9	1.0	0.6	3.5

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

ARRW = Air-Launched Rapid Response Weapon (being developed by the Air Force); HACM = Hypersonic Attack Cruise Missile (being developed by the Air Force); HALO = Hypersonic Air-Launched Offensive Antisurface Warfare missile (being developed by the Navy); IR-CPS = Intermediate-Range Conventional Prompt Strike missile (being developed by the Navy); km = kilometers; LRHW = Long-Range Hypersonic Weapon (being developed by the Army); MaRVs = maneuverable reentry vehicles; n.e. = not estimated; SM = Standard Missile (the SM-6 Block IB is being developed by the Navy as a variant of the existing Block IA).

- a. Includes costs to procure the missiles and associated equipment, costs to assemble and integrate the individual missile components, and costs to test that the assembly and integration have been done correctly. (Costs to integrate the missiles onto their launch platforms are included under “platform integration.”)
- b. Excludes costs to develop the missiles.
- c. Includes the costs of ground vehicles for five Army missile batteries and costs for the Navy to integrate the missiles onto its three Zumwalt class destroyers.
- d. CBO estimated the costs of two versions of this option: one with 300 missiles, the same as the number of hypersonic LRHW/IR-CPS missiles in Option 1, and one with 100 missiles to reflect the fact that the air-launched weapons in this option would not need to be spread among ships and submarines in different parts of the world but could be stored in a few locations and flown to where they were needed on short notice. Thus, a smaller number of the air-launched hypersonic missiles in this option could provide a worldwide availability similar to that provided by the larger number of ground- or sea-launched hypersonic missiles in Option 1.
- e. Includes integration only with B-52 bombers.
- f. The Department of Defense is early in the process of developing this missile. Little is known about its characteristics, so CBO did not have a basis for estimating the cost of the missile.

The SM-6 Block IB ballistic missiles in Option 5 would cost the least per missile, \$6 million, and the least overall, \$3.5 billion.

Air-launched missiles, like those in Options 3 and 4, offer DoD the flexibility to move missiles quickly to where they are needed. Because of that flexibility, fewer air-launched missiles could potentially provide a worldwide availability similar to that of a larger number of ground- or sea-launched missiles, which are bound to

the locations of their launch platforms. Smaller procurement quantities would increase the average cost per missile in Options 3 and 4 but would reduce the overall cost of the options. For example, reducing the number of hypersonic missiles in Option 3 to 100 would reduce the total cost of that option from \$5.3 billion to \$2.2 billion.

For the hypersonic missiles that are furthest along in development, the Army and Navy’s LRHW/IR-CPS (Option 1) and the Air Force’s ARRW (Option 3),



CBO produced its own estimates based on analogies with existing missiles or on established cost-estimating relationships for missile components, such as boosters. As a check on those estimates, CBO compared its results with the limited cost information provided by DoD. CBO used a similar approach to estimate the cost of the intermediate-range ballistic missiles in Option 2. For the SM-6 Block IB missiles in Option 5, CBO relied on estimates by the Navy, because the Block IB is a modification of a missile that is currently in production and for which the Navy has provided cost estimates.

Significant uncertainty exists about the costs of less mature technology and components related to hypersonic weapons, especially because developing them requires long-term investment in a wide variety of research areas that are associated with high risks of cost and schedule overruns. In particular, continued or increased amounts of research spending on aerothermodynamics and guidance systems might be necessary to achieve DoD's original goal of developing hypersonic missiles that can strike relocatable (or perhaps even moving) targets. For each option, the estimated costs described here represent one possible outcome based on the specific assumptions made in the option about the missiles' technologies and capabilities.

Effectiveness of the Options

Each of the missile systems in CBO's illustrative options would offer capabilities that would be relevant in the A2/AD and other scenarios described in Chapter 2. The intermediate-range hypersonic boost-glide missiles and ballistic missiles in Options 1 and 2 would provide similar range, responsiveness, and survivability against current and emerging threats. The air-launched weapons—the medium-range hypersonic boost-glide missiles in Option 3 and the hypersonic cruise missiles in Option 4—would have shorter ranges and would rely on aircraft to get closer to their targets, which would increase both flexibility in positioning and the vulnerability of their launch platforms. Like the air-launched missiles, the ground- or sea-launched ballistic missiles in Option 5 would have short range and would complement the intermediate-range options.

Option 1: Intermediate-Range, Ground- or Sea-Launched Hypersonic Boost-Glide Missiles (Similar to LRHW/IR-CPS)

Launched from Guam, an intermediate-range boost-glide missile like the ones in Option 1 would be able

to reach coastal regions of mainland China (a range of 3,000 km) in less than 15 minutes, CBO calculates. If the launchers were at the ready, it might take only about 5 minutes to launch the weapons once ordered to do so, for a total response time of 20 minutes. That rapid a response would require ground-based launchers to be deployed and ready to fire and submarines or surface ships to be within range and ready to launch.

Any additional steps that the launch platforms needed to take before being in range or ready to launch would add to the response time. For example, a ground-based launch system might take as much as 30 minutes to set up before it could fire a missile. A submarine located within 3,000 km of shore would be able to launch within a much shorter time, perhaps 5 minutes, provided that it was ready to fire. Thus, in a scenario in which mobile launchers were based on Guam and submarines were located about the same distance away from China, the intermediate-range boost-glide missiles in Option 1 could provide some of the fastest strike options from long distances early in a conflict. (If submarines were located closer to their targets than Guam, their missiles would arrive even sooner.)

The first-generation hypersonic boost-glide missiles that DoD is working on now will not be able to maneuver in response to movement by their targets. Therefore, the set of targets those missiles could attack would be limited to targets that were fixed or likely to remain fixed for at least 30 minutes. The targets would probably need to stay fixed for much longer than 30 minutes because it takes time (many minutes or longer) for U.S. intelligence, surveillance, and reconnaissance systems to find targets, confirm what they are, and transmit the information to regional commanders, as well as time for a commander's launch order to be disseminated to the crew operating the missile launcher. That set of targets would probably include coastal anti-aircraft and anti-ship defensive systems (including missiles and sensors) and command or communications nodes. A successful strike on such targets could reduce, though not eliminate, the risks to U.S. aircraft and surface ships operating in the defended region. The ability to reach targets inland would depend on the maximum range of a missile and where it was launched from.

Given the high speed and low and unpredictable trajectory of an intermediate-range boost-glide missile, it would be difficult for an adversary to intercept the

missile before it reached its target, according to CBO's analysis (unless the adversary developed hypersonic missile defenses at some future time). The launch platforms, however, might be vulnerable to attack by intermediate-range ballistic missiles and bombers, because Guam is within reach of those systems and because launching a missile from a ship or aircraft could reveal its location. The head of DoD's Indo-Pacific Command has stated that the missile defense system currently in place on Guam (a single Terminal High-Altitude Area Defense battery) leaves bases there vulnerable. DoD plans to explore adding a more capable missile defense system (the Aegis Ashore system) on Guam as part of its broader Pacific Deterrence Initiative.

Ground-based launchers would probably be more survivable in the Baltic region than on Guam, mostly because they would have many areas from which to operate. Aircraft based relatively near the conflict zone could also have many airfields to operate from. Those conditions would greatly increase the effectiveness of ground- or air-launched boost-glide missiles in a Baltic scenario. Hypersonic missiles launched from submarines and surface ships would probably not play as large a role in the Baltic region, given the alternative land- and air-basing options.

Option 2: Intermediate-Range, Ground- or Sea-Launched Ballistic Missiles Equipped With MaRVs

The ballistic missiles equipped with maneuverable reentry vehicles in Option 2 would offer roughly the same effectiveness as the hypersonic boost-glide missiles in Option 1 in both the China and Baltic scenarios. The two types of missiles would have the same range and reach targets just as quickly. The main difference is that the ballistic missiles would need to be able to defeat midcourse-phase ballistic missile defenses—if potential U.S. adversaries developed such systems in the coming decades that could contend with U.S. countermeasures. (Midcourse defenses designed to counter ballistic missiles would pose little threat to hypersonic boost-glide missiles because of their lower trajectories.) It is not clear whether there would be much difference in the ability of MaRVs or hypersonic glide bodies to penetrate short-range (terminal-phase) defenses located close to a target.

Because MaRVs are likely to be lighter than hypersonic glide bodies, the ballistic missiles in Option 2 could be designed to have longer ranges or larger payloads than

the boost-glide missiles in Option 1. They could also be designed to fly alternative ballistic trajectories, such as depressed trajectories, that would increase their survivability. MaRVs would allow the missiles to be just as accurate as hypersonic weapons, permit them to execute maneuvers to avoid terminal-phase defenses, and let them be retargeted during flight. In addition, a MaRV would enter the terminal phase of flight at a higher speed than a boost-glide missile, which would shorten the time a terminal defense system had to intercept it. However, as with hypersonic missiles, any maneuvers that a MaRV made would reduce its speed.

Option 3: Medium-Range, Air-Launched Hypersonic Boost-Glide Missiles (Similar to ARRW)

The shorter range of the hypersonic-boost glide missiles in Option 3 means that aircraft would have to fly well within the range of China's or Russia's A2/AD defenses during a conflict to launch them. In addition, because of the travel time necessary to position the aircraft, the missiles' effectiveness would depend on the number of aircraft in the general region early in the conflict.

The medium-range hypersonic boost-glide missiles would probably also travel more slowly than their intermediate-range counterparts in Options 1 and 2, though still within the hypersonic regime (about Mach 7, on average, over the course of their flight, CBO estimates). CBO's analysis indicates that from launch, a medium-range hypersonic boost-glide missile could reach its maximum range of roughly 1,000 km in less than 15 minutes. It would probably also maintain a lower altitude early in flight than an intermediate-range hypersonic missile and would reach a lower apogee, making it even harder for ground-based radar to detect.

In a China scenario, medium-range, hypersonic boost-glide missiles would not be effective at reaching deep inland targets, because of their limited range. In a Baltic scenario, depending on the basing location, the ability to launch multiple missiles from a relatively short standoff distance could offer advantages to the United States in a conflict with Russia.

Option 4: Short-Range, Air-Launched Hypersonic Cruise Missiles (Similar to HACM/HALO)

In both the Pacific and Baltic scenarios, the effectiveness of the short-range hypersonic cruise missiles in Option 4

would be similar to that of the medium-range hypersonic boost-glide missiles in Option 3. The cruise missiles' even shorter range would increase the time that aircraft carrying the missiles would have to spend in defended areas. But if the cruise missiles were smaller, aircraft could carry more of them, increasing coverage of a given area.

CBO projects that hypersonic cruise missiles' range would be less than 1,000 km (probably closer to 500 km) and that their speed would be in the low hypersonic regime (between Mach 5 and Mach 9). Hypersonic cruise missiles would travel at lower altitudes than hypersonic boost-glide missiles for almost all of their flight, making them more difficult to track.

Option 5: Short-Range, Ground- or Sea-Launched Ballistic Missiles (Similar to SM-6 Block IB)

The short-range ballistic missiles in Option 5 would not be able to reach China if launched from Guam. Thus, in the Pacific scenario, they would not play a large role if U.S. forces had to operate from long distances during the initial phase of a conflict, unless they could be launched from Okinawa, the Japanese mainland, or Taiwan. However, previous analysis by CBO concluded that ground-launched SM-6 missiles might be effective for defending U.S. bases and the territory of U.S. allies in the Pacific.² For that mission, they might operate as antiship or air-defense weapons.

Launched from a surface ship, the upgraded SM-6 missiles in Option 5 would only reach the coast of China if the ship was located within the A2/AD zone, thus requiring protection. Alternatively, as a sea-launched

antiship missile, the SM-6 Block IB might be effective at destroying China's ship-based A2/AD assets.

In a Baltic scenario, a short-range, ground-launched ballistic missile like the upgraded SM-6 would have more applications. The ship-launched variant would be less useful, however, given the likely contested zone in the Baltic Sea.³

Pursuing Multiple Options

None of the options that CBO examined are mutually exclusive; lawmakers could opt to pursue several of them at once. DoD's current multipronged approach to developing hypersonic missiles has some advantages—because of the broad range of potential scenarios in which different weapons could be used—despite its higher cost than a single-pronged approach.

For example, ground-launched, intermediate-range hypersonic boost-glide missiles (Option 1) or ballistic missiles equipped with MaRVs (Option 2) would probably provide the quickest response times. But in a Pacific scenario, they would provide less coverage of targets in China than other types of missiles would. That means ground-launched missiles could be most relevant in the first phase of battle and could open access for sea- and air-launched missiles by destroying some defenses. Submarines could also provide initial strikes with hypersonic missiles if they were within range of their targets.

Air-launched medium-range weapons (like the boost-glide missiles in Option 3) would become more useful after an adversary's A2/AD systems had been significantly degraded. Those air-launched weapons would also provide shorter response times once the aircraft could loiter safely within range of their targets.

2. See Congressional Budget Office, *Options for Fielding Ground-Launched Long-Range Missiles* (February 2020), www.cbo.gov/publication/56068.

3. Ibid.

Appendix A: Other Military Research Programs Related to Hypersonic Flight

Besides the missile development programs discussed earlier in this report, the Department of Defense (DoD) funds a number of programs that focus on more basic or applied research involving hypersonic flight. Those programs are being pursued by the Defense Advanced Research Projects Agency (DARPA) and in both military and academic laboratories. The technical areas that those programs focus on provide insight into the remaining challenges for fielding hypersonic missiles with advanced capabilities.

Between them, DARPA's and the military services' budgets include dozens of program elements that involve basic research, applied research, or advanced technology development relevant to hypersonic weapons. Some illustrative examples are described below. Basic research includes projects at military laboratories and universities to develop a better understanding of the performance of advanced materials and the complex air-flow phenomena of hypersonic flight. Applied research includes efforts to bring various materials and components of hypersonic missiles to maturity and to develop methods for producing those materials and components cost-effectively. Overarching goals for such research include increasing missiles' range, payload capacity, speed, and maneuverability and reducing costs and processing time for components.

The services and DoD are also funding research into technological advances necessary for the complex command-and-control systems and the surveillance and reconnaissance capabilities that would be essential for defending against adversaries' hypersonic missiles. Those research efforts are not included here.

Defense Advanced Research Projects Agency

DARPA continues to contribute to the Air Force's boost-glide missile program through its research on the Tactical Boost Glide vehicle described in Chapter 1. In addition, DARPA has several research programs exploring

materials that can perform at high temperatures—specifically, materials that could be used for the structures of hypersonic missiles or for radomes (transparent areas through which radio signals can travel). Those programs are investigating materials that can provide thermal protection as well as structural components that can withstand the thermal loads that hypersonic boost-glide missiles are subject to.

As part of its efforts to support development of hypersonic cruise missiles, DARPA is also investigating propulsion techniques and cost-effective system designs under the Hypersonic Air-Breathing Weapon Concept (HAWC) program, now called MoHAWC. The program received additional appropriations in 2022 to complete flight tests.

Service Programs

Like DARPA, the Air Force and Navy are investing in research to develop materials that have a combination of properties that could make them suitable for use in hypersonic weapons. Those research efforts include development of processing methods to generate potential materials and computational methods to simulate the materials' performance.

Several services are conducting research into aerodynamics at hypersonic speeds. For example, the Navy is developing simulation tools to model the aerodynamics of hypersonic bodies (including a program exploring their interactions with cloud formations). The Army is investigating the aerodynamics of various shapes at hypersonic speeds and developing models to predict the effects of turbulence.

In addition, the Army's Foundational Hypersonics Weapons Research program focuses on the fundamental physics of air flows, the mechanics of maneuver control, vehicle shapes, and computational and experimental techniques, as well as ways to reduce processing costs for carbon-carbon composites. The Navy's overarching

Hypersonic Technologies program is intended to fund novel ideas for advancing the performance of hypersonic weapons in areas such as advanced materials, propulsion, stability and control, seekers and sensors, guidance, navigation, and payloads.

At a higher level of technological development, the Army's Advanced Hypersonic Technology program continues to support development of the Long-Range Hypersonic Weapon and advanced technologies to incorporate into that missile. The Army is also investing in test infrastructure (such as wind tunnels), high-temperature electronics, and high-performance computing in service of hypersonic applications. The Air Force is likewise focusing on inserting advanced technology into high-speed systems through a research program to develop simulation and test-bed technology to make technology insertion less risky for hypersonic missile programs. In addition, the Air Force is developing hardware-in-the-loop test beds for novel guidance concepts as part of its research into advanced guidance technology applicable to hypersonic missiles.

For its part, the Air Force is conducting computational research to fully characterize the challenges that conventional warheads face during hypersonic flight, including

thermal and vibration issues. And the Marine Corps is funding research to develop a design for a hypersonic munition compatible with the M142 High Mobility Artillery Rocket System (HIMARS).

In the area of hypersonic cruise missiles, the Air Force continues to fund research exploring engine components and aerodynamic design to improve the efficiency and operability of scramjets, in addition to its program to develop the Hypersonic Attack Cruise Missile. (The Navy's applied research program for scramjet technology, the Hypersonic Booster program, has been terminated for 2023 and funding redirected to the service's Hypersonic Air-Launched Offensive Antisurface Warfare program.) Further, both the Air Force and the Navy are conducting research into advanced and alternative fuels that have the potential to improve scramjets' speed and performance.

Rapid and affordable manufacturing of hypersonic missile components also remains a challenge across the services. The Air Force is funding a program to develop manufacturing technology for materials, command-and-control communications components, and radio-frequency and digital components for hypersonic missiles.

Appendix B: CBO's Approach to Modeling Missile Trajectories

To estimate the flight times of different types of missiles and their visibility to radar, the Congressional Budget Office used analytic models of the missiles' trajectories. In modeling those flight paths, CBO had two goals. The first was to estimate flight time as a function of range and of parameters such as the speed of a rocket when its booster stops burning (known as the burnout speed). The second was to model the visibility of a missile to ground-based radar as a function of altitude. This appendix provides details about the models CBO used.

Flight Time

The time a missile spends in flight depends on its trajectory, the range to its target, and its speed. A missile's speed in turn depends on the initial burnout speed and the deceleration associated with reentry, maneuvering, and atmospheric drag when the missile flies through the air.

Trajectory Considerations

CBO considered four types of missile trajectories: the minimum-energy trajectory and a depressed trajectory for ballistic missiles (see the figure in Box 1-1 on page 6), the boost-glide trajectory for hypersonic missiles, and the flat, low-altitude trajectory for cruise missiles. The minimum-energy trajectory (MET) is the flight path that maximizes the total range of a missile on a ballistic trajectory for a given amount of energy input. CBO used the MET as a baseline for ballistic flights of a given range. For comparison, CBO also considered a lower-altitude ballistic trajectory. That depressed trajectory requires more energy than the MET for the same range, but a missile on such a path flies a shorter distance and thus can arrive at its target faster than a missile on the MET.

For hypersonic boost-glide missiles, common depictions of trajectories by the Department of Defense (DoD) and others suggest that a missile's glide body reenters the atmosphere very shortly after the booster rocket stops burning and spends almost all of its trajectory inside the atmosphere. During the time spent inside the atmosphere, the glide body will be difficult to detect by

ground-based radar because of its altitude and will be able to maneuver using control surfaces to interact with the air. (Missiles that are outside the atmosphere must rely on thrusters to change their flight path.)

Despite those advantages, CBO's analysis suggests that for the foreseeable future, boost-glide missiles that travel more than 1,000 kilometers (km) are unlikely to spend more than half of their flight inside the atmosphere because of the intense thermal stresses of hypersonic flight through air. Specifically, the longer a glide body spends interacting with the atmosphere at hypersonic speeds, the more thermal stress it will endure. Trajectory designs that balance those competing incentives (difficulty of detection and maneuverability on the one hand and thermal stress on the other hand) will result in hypersonic boost-glide missiles that spend roughly half of their flight gliding within the atmosphere. Such a trajectory also avoids constraints on missiles that were imposed by the Intermediate-Range Nuclear Forces (INF) treaty, which prohibited missiles that spent more than 50 percent of their flight on a ballistic trajectory. The INF treaty is no longer in effect, but some of the programs that DoD is working on today were under development when the treaty was still in force.

Given the thermal challenges of hypersonic flight, it is unclear exactly how much of a boost-glide missile's trajectory is likely to be on a ballistic path and how much will be spent on a glide path inside the atmosphere. The longer the range of a boost-glide missile, the more likely it is to spend a larger fraction of its flight outside the atmosphere. To address that uncertainty, CBO modeled the boost-glide trajectory using two different values for the time spent on a ballistic path. In the lower case, the missile spends half of its flight on a ballistic path and the other half inside the atmosphere in the glide phase. Potential improvements in thermal design could enable longer glide times, so CBO also explored the effects of decreasing the amount of the flight spent on a ballistic path to one-quarter of the range. That trajectory would allow the missile to remain at low

altitudes longer, but at the cost of a longer total flight time than a trajectory in which the glide phase was limited to only half of the flight.

Calculating Flight Times for Minimum-Energy and Depressed-Trajectory Ballistic Missiles

CBO estimated flight times for a ballistic missile on a minimum-energy trajectory using Python code shared with CBO by David Wright of the Massachusetts Institute of Technology. The code is a physics-based model for flight on a round, nonrotating Earth with atmospheric drag.¹ In the model, the equations of motion—including thrust, gravitational, and atmospheric drag forces—are integrated to calculate the position and speed of a missile throughout its flight. The output of the model is the flight time after burnout and the burnout speed. CBO estimated the time until the booster burns out by using data for known missiles of similar ranges and linearly interpolating between those data.

To estimate flight times for the depressed trajectory, CBO considered the effect of the shorter path that a missile on a depressed trajectory travels as well as the potential for using a larger rocket booster with a higher burnout speed. CBO estimated that flight times for a ballistic missile on the depressed trajectory could be 10 percent to 30 percent shorter than flight times on the MET.²

Calculating Flight Times for Hypersonic Boost-Glide Missiles

The dynamics of flight through the atmosphere at hypersonic speeds require complex physical models to simulate. The aerodynamic properties of DoD's prototype hypersonic missiles are not publicly available. Thus, for the glide phase of the trajectory, CBO started with the results from an earlier analysis of a test that the United States conducted on the Hypersonic Technology Vehicle-2 (HTV-2) in 2008 and varied several parameters to reflect potential design choices and improvements in glide bodies' aerothermodynamic properties made

since the HTV-2 was tested.³ CBO did not use a detailed model of the aerodynamics of hypersonic flight.

Burnout Speed, Apogee, and Deceleration. The speed at which the glide body enters the ballistic (midcourse) portion of the flight is a function of the burnout speed of the rocket booster. CBO does not know the burnout speeds of the rocket boosters intended to be used for the Army's Long-Range Hypersonic Weapon (LRHW), the Navy's Intermediate-Range Conventional Prompt Strike (IR-CPS), or the Air Force's Air-Launched Rapid Response Weapon (ARRW), so CBO used two values for the burnout speed in its modeling:

- The burnout speed associated with a ballistic missile on a minimum-energy trajectory of the same range as a given boost-glide missile (called the MET-equivalent boost), and
- The burnout speed associated with the HTV-2 (6 km per second) regardless of a missile's range.

CBO chose those values to cover a wide range of potential booster choices. Competing demands on booster design include size and cost, thermal challenges associated with the glide speed, and flight time. However, factors such as the diameter and depth of the missile tubes in the new payload module for Virginia class submarines can limit options for using larger boosters.

The glide bodies under development in the LRHW, IR-CPS, and ARRW programs have been reported to reach significantly lower apogees (maximum altitudes) than the apogees associated with ballistic trajectories.⁴ To divert from a ballistic path, reenter the atmosphere, and begin gliding at hypersonic speeds, a missile must undergo a maneuver to reorient it toward Earth. In addition, the glide body will lose speed as it reenters the atmosphere, and once inside the atmosphere, it will continue to slow because of atmospheric drag as it travels along its flight path.

1. For more information about the physics of ballistic missiles, see Albert D. Wheelon, "Free Flight of a Ballistic Missile," *American Rocket Society Journal*, vol. 29, no. 12 (December 1959), pp. 915–926, <https://doi.org/10.2514/8.4944>.

2. Those estimates are based on Lisbeth Gronlund and David C. Wright, "Depressed Trajectory SLBMs: A Technical Evaluation and Arms Control Possibilities," *Science & Global Security*, vol. 3, no. 1–2 (1992), pp. 101–159, <https://tinyurl.com/2p8jnb48>.

3. See James M. Acton, "Hypersonic Boost-Glide Weapons," *Science & Global Security*, vol. 23, no. 3 (2015), pp. 191–219, <https://tinyurl.com/yc79ph7x>; and Cameron L. Tracy and David Wright, "Modelling the Performance of Hypersonic Boost-Glide Missiles," *Science & Global Security*, vol. 28, no. 3 (2020), pp. 135–170, <https://tinyurl.com/3upn3pk2>.

4. Officials from the Office of the Under Secretary of Defense for Research and Engineering, personal communication with CBO staff (March 11, 2021).

CBO used the deceleration observed in the model for a ballistic missile to estimate the deceleration of a hypersonic glide body when it performs the maneuver to reorient itself and reenters the atmosphere. CBO estimates that speed decreases by roughly 20 percent when a glide body goes below an altitude of 100 km and reenters the atmosphere. For simplicity, CBO considers that decrease in speed as occurring instantaneously. For the remainder of a flight, CBO modeled two glide phases: one in the upper atmosphere and one in the lower, denser atmosphere, where drag has a more significant impact. The altitude of the glide body is assumed to follow a linear descent in each phase, from 100 km to 40 km in the upper atmosphere and from 40 km to 30 km in the lower atmosphere. To estimate the deceleration profile of a glide body in each phase, CBO performed linear fits on published model results of the glide phase for a variety of initial speeds.⁵

CBO's model for a glide body's velocity in the direction of motion reflects the net effect of lift, drag, and gravity by using a consistent reduction in velocity of 0.2 km/sec for every 1,000 km of range in the upper atmosphere and 0.8 km/sec for every 1,000 km of range in the lower atmosphere. Those values are consistent with other models of hypersonic boost-glide missiles.⁶ To reflect potential improvements in glide-body design that would reduce drag, CBO also considered a "low-drag" design in which deceleration is half that of the baseline values: a consistent reduction in velocity of 0.1 km/sec for every 1,000 km of range in the upper atmosphere and 0.4 km/sec percent for every 1,000 km of range in the lower atmosphere.

How Different Values Affect Flight Times. Altering properties such as the trajectory, drag, and burnout speed of a boost-glide missile affects the missile's time to reach its target. Those effects are greater the longer the range to the target. At a range of 10,000 km, for example, the flight time of a missile with a MET-equivalent boost and baseline drag increases from 35.8 minutes to 42.0 minutes when the glide phase increases from 50 percent to

75 percent of the trajectory (see Figure B-1, left-hand panels). For a missile with a 6 km/sec boost and baseline drag, the same change increases the time to fly 10,000 km by more than 10 minutes, from 44.3 minutes to 54.4 minutes.

Reducing the effective drag (moving from the baseline-drag scenario to the low-drag scenario) has a relatively small effect on the flight time of a boost-glide missile. That difference is more pronounced—but still small—when the glide phase increases, whether because the missile's overall range is longer or because the glide phase is lengthened to 75 percent of the missile's trajectory.

The hypersonic boost-glide missiles that DoD is currently developing are likely to have ranges between roughly 500 km and 4,000 km. At those ranges, CBO's model predicts that differences in the percentage of the glide phase and in drag would have minimal effects on flight times (see the area inside the black dashed lines in Figure B-1). For a missile with a MET-equivalent boost, increasing the glide phase from 50 percent to 75 percent of the trajectory does not increase the flight time at 1,000 km and increases it by roughly 30 seconds at 4,000 km. Reducing the drag factor by half shortens that missile's flight time by just a few seconds at short ranges and by about one minute at 4,000 km if the missile's glide phase lasts for 75 percent of the trajectory.

Differences in initial speed (a MET-equivalent or 6 km/sec burnout speed) have the greatest effect on flight time of the variables included in CBO's modeling. A burnout speed of 6 km/sec is the speed associated with a MET flight with a range of about 5,700 km. Below that range, the 6 km/sec burnout speed is faster than the MET-equivalent boost; above that range, it is slower. Using a 6 km/sec booster at ranges greater than 5,700 km results in flight times that are significantly longer than for ballistic trajectories. CBO believes it is unlikely that such ranges are being considered for hypersonic boost-glide missiles, because of the thermodynamic challenges of such long flights and the slow speed at which a glide body would be traveling as it neared its target. Even so, a single rocket booster with a 6 km/sec burnout speed would not be appropriate to span the full set of ranges considered here.

At a range of 1,000 km and with baseline deceleration because of drag, increasing the burnout speed from the MET equivalent to 6 km/sec would reduce a missile's

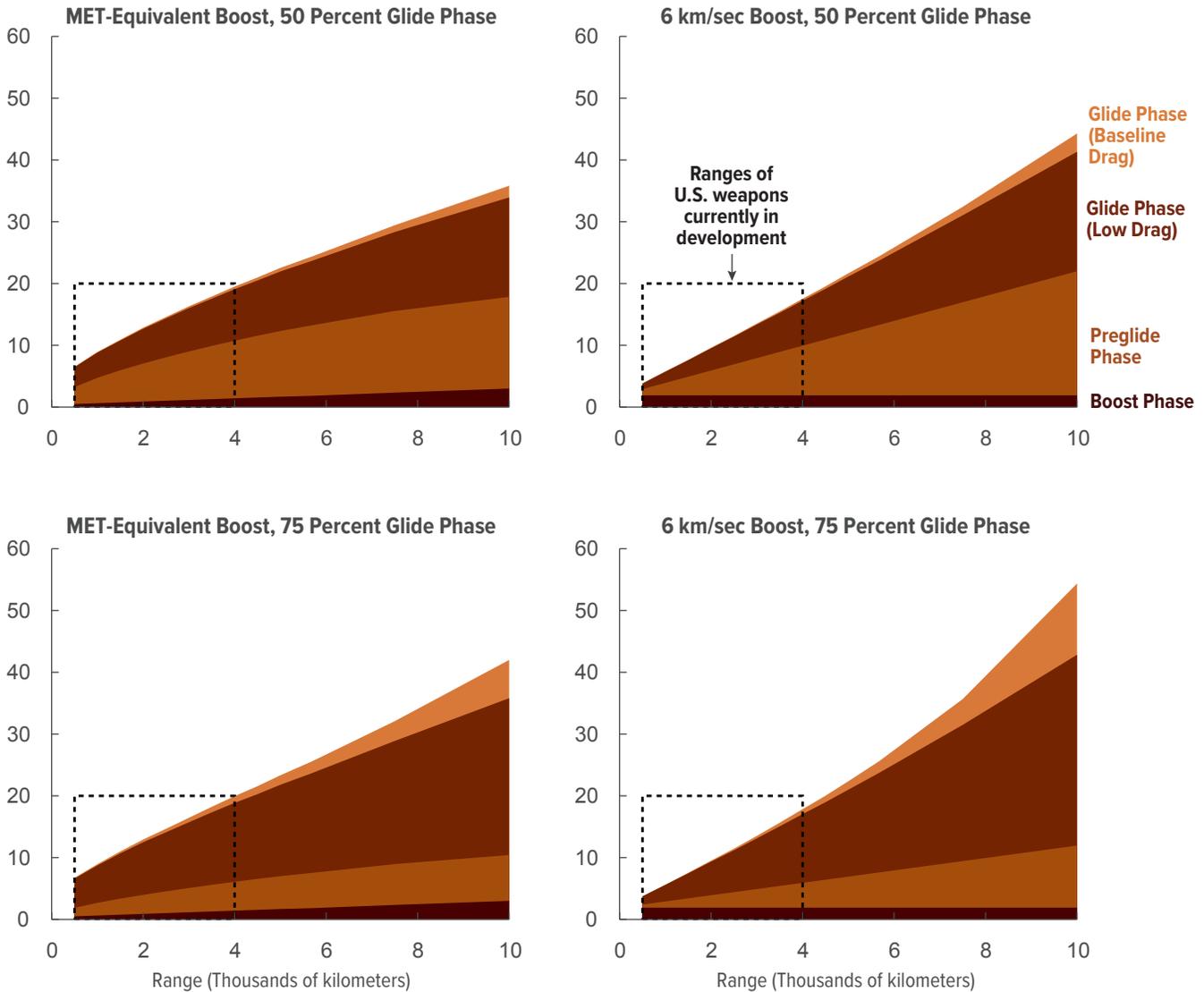
5. See James M. Acton, "Hypersonic Boost-Glide Weapons," *Science & Global Security*, vol. 23, no. 3 (2015), pp. 191–219, <https://tinyurl.com/yc79ph7x>; and Cameron L. Tracy and David Wright, "Modelling the Performance of Hypersonic Boost-Glide Missiles," *Science & Global Security*, vol. 28, no. 3 (2020), pp. 135–170, <https://tinyurl.com/3upn3pk2>.

6. See Cameron L. Tracy and David Wright, "Modelling the Performance of Hypersonic Boost-Glide Missiles," *Science & Global Security*, vol. 28, no. 3 (2020), pp. 135–170, <https://tinyurl.com/3upn3pk2>.

Figure B-1.

Flight Times for a Hypersonic Boost-Glide Missile, by Phase of Flight, Range, and Design Parameters

Minutes



The effect of initial speed (a MET-equivalent or 6 km/sec burnout speed) is the most significant difference between the options that CBO modeled. At ranges greater than 6,500 km, flight times are longer with a 6 km/sec boost than with a MET-equivalent boost. The more of a flight spent in the glide phase—because of either trajectory design or longer overall range—the greater the impact of drag conditions.

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

Total flight time for a hypersonic boost-glide missile is the sum of the three phases of the missile’s flight. For a missile with an initial boost equivalent to that of a ballistic missile on a minimum-energy trajectory of the same range, the boost phase varies as a function of range. For a missile with a baseline boost of 6 km/sec, the boost phase is constant across all ranges. The preglide phase (the period after boost and before reentering the atmosphere) is a function of the trajectory design—specifically, whether 50 percent or 75 percent of the distance traveled is spent in the glide phase. The glide phase is represented by either the dark brown area (for the low-drag design) or by the orange and dark brown areas together (for the baseline-drag design).

The black dashed box represents the anticipated ranges of the U.S. hypersonic boost-glide missiles currently in development: the Air Force’s Air-Launched Rapid Response Weapon, the Navy’s Intermediate-Range Conventional Prompt Strike missile, and the Army’s Long-Range Hypersonic Weapon.

km/sec = kilometers per second; MET = minimum-energy trajectory.



Table B-1.

Estimated Flight Times for Hypersonic Boost-Glide Missiles Under Various Conditions

Minutes

Range (km)	MET-Equivalent Boost				6 km/sec Boost			
	50 Percent Glide Phase		75 Percent Glide Phase		50 Percent Glide Phase		75 Percent Glide Phase	
	Baseline Deceleration	Low-Drag Deceleration						
	500	6.5	6.5	6.7	6.6	3.8	3.8	3.7
1,000	8.9	8.8	8.9	8.7	5.7	5.7	5.6	5.6
1,500	10.9	10.8	11.0	10.7	7.6	7.6	7.5	7.4
2,000	12.9	12.7	12.9	12.5	9.6	9.5	9.5	9.3
2,500	14.6	14.4	14.7	14.1	11.5	11.4	11.4	11.2
3,000	16.3	16.0	16.4	15.7	13.5	13.4	13.5	13.1
3,500	17.9	17.5	18.2	17.3	15.5	15.2	15.6	15.1
4,000	19.5	19.1	20.0	18.9	17.5	17.2	17.8	17.0
4,500	21.0	20.5	21.6	20.3	19.5	19.1	20.0	19.0
5,000	22.5	22.0	23.3	21.8	21.7	21.1	22.4	21.0
7,500	29.4	28.3	32.1	28.9	32.4	31.0	35.7	31.5
10,000	35.8	33.9	42.0	35.8	44.3	41.3	54.4	42.8

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

CBO calculated the flight times for hypersonic boost-glide missiles under a wide range of possible conditions and missile properties. The missiles' range varied from 500 km to 10,000 km. The burnout speed of the rocket was modeled under two conditions: a boost equivalent to that of a ballistic missile on a minimum-energy trajectory of the same range, and a baseline boost of 6 km/sec over all the ranges. Under each of those conditions, the trajectory was modeled using a glide phase that lasted either 50 percent or 75 percent of the total range and using a baseline deceleration profile as well as a low-drag deceleration profile that slowed the glide body less.

km/sec = kilometers per second; MET = minimum-energy trajectory.

flight time by more than 3 minutes, about half the total resulting flight time with a 50 percent glide phase (see Table B-1). At 4,000 km, the reduction in time would be similar, 2 minutes, but that savings represents a much smaller percentage reduction in the total flight time. At 10,000 km, the MET-equivalent burnout speed is higher than 6 km/sec, so reducing the speed to 6 km/sec would increase the flight time by more than 5 minutes.

Comparing Flight Times for Ballistic Missiles and Hypersonic Boost-Glide Missiles

CBO compared its estimates of flight times for ballistic missiles on minimum-energy or depressed trajectories and hypersonic boost-glide missiles over different distances (see Figure 3-1 on page 28, lower panel). Both depressed-trajectory ballistic missiles and hypersonic boost-glide missiles have a variety of possible parameters, so CBO calculated a range of potential flight times for both types of missiles. For depressed-trajectory missiles, the top of the range of flight times for a given distance represents the MET burnout speed but with a shallower burnout angle (the angle above the horizon at which the

missile is moving at burnout), and the bottom of the range represents a higher burnout speed and an even shallower burnout angle. For hypersonic boost-glide missiles, at distances of less than 5,700 km, the top of the range of flight times represents glide bodies with baseline drag that are launched with a boost equivalent to that of a ballistic missile on a MET, and the bottom of the range represents glide bodies with half the baseline drag that are launched with a 6 km/sec boost. At distances of more than 5,700 km, the relative positions of the two burnout speeds are reversed.

CBO found that depressed-trajectory ballistic missiles generally have the shortest flight times over all distances, although hypersonic boost-glide missiles could have comparable flight times at distances of less than 1,000 km if they have a low-drag design and are launched by a 6 km/sec booster. CBO also found that ballistic missiles on a minimum-energy trajectory have shorter flight times than hypersonic boost-glide missiles at distances greater than about 5,000 km. At shorter distances, their flight times fall within the range of flight



times estimated for hypersonic boost-glide missiles. Only when glide bodies have less drag than is likely for the current generation of U.S. hypersonic missiles, and are launched on very fast boosters over short ranges, do hypersonic boost-glide missiles have a clear time advantage over ballistic missiles on a minimum-energy trajectory.

Calculating Flight Times for Cruise Missiles

CBO modeled the flight times of cruise missiles using three bands of speed: Mach 0.5 to 1 for subsonic, Mach 1 to 5 for supersonic, and Mach 5 to 9 for hypersonic. CBO assumed a completely flat trajectory for cruise missiles to calculate flight time as the ratio of range to velocity. The maximum range of a cruise missile is limited by the amount of fuel it can carry. CBO estimated those maximum ranges at 2,000 km for a subsonic cruise missile, 1,000 km for a supersonic cruise missile, and 500 km for a hypersonic cruise missile.

Radar Visibility

CBO also analyzed how different types of trajectories can affect how soon in its flight a missile is visible to ground-based radar. The horizon of a radar is a simple geometric calculation that takes into account the curvature of the Earth in order to estimate the distance at which a radar can detect an object at a certain height above the Earth. The basic calculation, which includes an effective radius of the Earth to account for the fact that the atmosphere tends to bend (refract) radio waves toward the Earth, is:

$$D = \sqrt{2 \times h \times \frac{4R_E}{3}}$$

Where D is the distance from the radar to the object and h is the height of the radar above the surface of the Earth, which has a radius R_E . To be detectable, any object beyond that distance must be above the Earth's surface at a minimum height of:

$$H_T = \frac{\left(R_T - \sqrt{2 \times h \times \frac{4R_E}{3}} \right)}{2 \times \frac{4R_E}{3}}$$

where R_T is the range to the target.

To estimate when a missile is above the radar horizon, CBO populated a matrix of heights and ranges for a 30-meter-high ground-based antenna and compared the trajectories modeled above with the condition for H_T to determine whether a missile at each point along its trajectory would be above the radar horizon and thus in view of the radar. CBO varied the height of the radar up to 100 meters (m) to determine the calculations' sensitivity to that parameter and found that the ranges at which various types of missiles could be detected did not change significantly. For example, a radar 100 m high could detect a missile about 20 km earlier in its flight than a radar 30 m high. For a missile traveling at Mach 10, that difference would translate to an additional 6 seconds of warning.

CBO used simple geometric calculations to illustrate the challenge of detecting low-flying missiles and aircraft from ground-based radar. Much more detailed modeling would be required to predict the performance of any given radar system. In general, air-defense radars lack the power to detect hypersonic glide bodies at the ranges considered in this analysis. More powerful radar systems may have that ability, but they still face a variety of challenges that constrain their performance, including clutter in the environment (such as radar returns from trees and other objects on the surface that are close to the horizon). Also, a radar usually has a minimum elevation angle that is at least a few degrees above the horizon, which limits how low it can see. CBO did not include that effect in its simple calculations, but the basic result would be the same: Objects that fly low remain below the radar horizon longer.

Appendix C: How CBO Estimated Costs for Weapons Included in This Analysis

The Congressional Budget Office examined several types of missiles that could help the U.S. military counter the antiaccess and area-denial environments being created by potential U.S. adversaries, particularly China and Russia. Those weapons include hypersonic boost-glide missiles based closely on the ones being developed by the Army, Navy, and Air Force; intermediate-range, ground- or sea-launched ballistic missiles (which would have a range similar to that of the Army’s and Navy’s planned boost-glide missiles); short-range, air- or sea-launched hypersonic cruise missiles; and short-range, ground- or sea-launched ballistic missiles like the Standard Missile-6 (SM-6) Block IB, an upgraded version of the Navy’s existing SM-6 Block IA missile.

CBO’s Approach

CBO estimated several types of costs for those weapon systems: costs to procure the missiles and associated equipment, costs to integrate a weapon system onto existing platforms (such as ships and aircraft), and costs to sustain the system after its deployment. Those costs are presented in 2023 dollars.

CBO’s estimates do not include costs to finish developing the missiles, for two reasons. First, the services are using nontraditional funding mechanisms to develop hypersonic missiles. That approach makes it difficult to determine how much development funding is being used for hypersonic technology in general, how much is being used to develop specific operational systems, and how much is being used for what would be considered procurement in a more traditional program. Second, given the relative immaturity of hypersonic weapons technology, the Department of Defense’s (DoD’s) estimates may be optimistic, but CBO does not have a good way to estimate likely development costs.

CBO based its estimates for surface- and air-launched hypersonic boost-glide missiles as closely as possible on publicly available information about the characteristics of, and procurement goals for, the three versions of

those missiles currently in development—the Army’s Long-Range Hypersonic Weapon (LRHW), the Navy’s Intermediate-Range Conventional Prompt Strike (IR-CPS) missile, and the Air Force’s AGM-183A Air-Launched Rapid Response Weapon (ARRW). Although CBO refers to those weapons as the “LRHW/IR-CPS” and “ARRW” missiles in this appendix for simplicity, CBO’s estimates are not intended to be predictions of the actual costs of those programs. (The full details of those systems are not publicly known, and the technology is still being developed, so CBO could not estimate costs with confidence.) Rather, CBO’s estimates are meant to illustrate the relative costs of various types of high-speed weapons.

For the hypersonic missiles that are furthest along in development—the LRHW, IR-CPS, and ARRW missiles—CBO based its estimates of costs on analogies with existing missiles or on established cost-estimating relationships for missile components, such as boosters. To check those estimates, CBO compared them with the limited cost information provided by DoD. CBO used a similar approach to estimate the costs of notional intermediate-range ballistic missiles with maneuverable reentry vehicles. CBO could not estimate the costs of hypersonic cruise missiles, because the technology for those missiles is at an early stage, and the ultimate cost to procure such a missile is unclear. For the SM-6 Block IB missile, CBO started its estimates with cost data provided by the Navy for the SM-6 Block IA, which is currently in production, and adjusted for the different characteristics of the IB variant.

CBO’s estimates represent one set of possible outcomes that reflect the specific assumptions made about missiles’ technologies and capabilities. Significant uncertainty exists about the costs of less mature technologies or missile components, which represent long-term investments in a wide variety of research areas that are associated with high risks of cost and schedule overruns.

Costs of Hypersonic Boost-Glide Missiles for the Army and Navy

The Army's LRHW system and the Navy's IR-CPS system will use essentially the same missiles but with different canisters to accommodate the missiles' different launch platforms—ground vehicles, submarines, and surface ships. (Canisters are the protective cases in which missiles are transported and sometimes launched.) The two services are jointly developing the LRHW/IR-CPS missile but are separately developing their own canisters and launchers.

Procurement Costs

To estimate the procurement cost of an LRHW/IR-CPS missile—including the booster, glide body, and canister—CBO used the costs of similar components for existing weapon systems, as well as published estimates from the LRHW and IR-CPS program offices for components of their systems. (Additional costs for the service-specific launchers and other equipment are discussed below with platform costs.)

Rocket boosters are a well-understood technology. Widely used cost models exist for boosters that are based on the performance parameters of existing systems. CBO identified a rocket similar in size to the one shown in drawings released by the LRHW and IR-CPS program offices: the Orion 32 family of boosters being developed by Northrop Grumman. The first stage of the LRHW appears to be about the same size as a first-stage Orion 32XL, and the second stage is roughly half the size of a second-stage Orion 32. To estimate the cost of the two-stage LRHW/IR-CPS booster, CBO applied cost-estimating relationships developed by Technomics (a defense-analytics consulting firm) to the general characteristics of the Orion 32 boosters, adjusting for known differences with the LRHW/IR-CPS.

For the nose cone, which sits atop the missile and protects the glide body during the first part of the missile's flight, CBO based its estimate on the nose cone for the SM-3 Block IIA missile, scaled up to reflect the greater size of the LRHW/IR-CPS nose cone.

For the Common Hypersonic Glide Body (C-HGB), which will be used in both the LRHW and IR-CPS missiles, CBO started with estimated costs for the Mk21A ballistic reentry vehicle that is being developed for the Ground-Based Strategic Deterrent, an intercontinental ballistic missile slated to replace the Minuteman III.

CBO adjusted the costs of the Mk21A to account for the larger size of the C-HGB, which CBO estimated from images released by the LRHW and IR-CPS program offices. CBO further adjusted those costs to account for the additional thermal protection that the C-HGB will need (because it will spend a much longer time than the Mk21A moving at high speed through the atmosphere) and for a guidance and control system to allow the C-HGB to follow its planned trajectory and accurately hit its target. (A ballistic reentry vehicle such as the Mk21A does not have a guidance system; instead, it relies on the missile that carries it to release it at a point in space where gravity will pull it toward its target.)

Both the LRHW and the IR-CPS will be launched from a canister that will also protect the missile during storage and transportation. The canister will be mounted in or on the launcher platform that will fire the missile. CBO based its estimate of the procurement cost for an LRHW/IR-CPS canister on the cost of canisters for the SM-3 missile (which is fired from the vertical launch system on Navy surface ships), with adjustments to account for the much larger size of the LRHW/IR-CPS missiles.

Like the SM-3, the LRHW is a "hot-launch" missile that leaves the canister under its own rocket power. In contrast, the IR-CPS can be hot-launched from surface ships but will be "cold launched" from submarines. In a cold launch, high-pressure gas forces the missile out of the canister before the missile's booster ignites. CBO had no basis to estimate how the costs of the two canisters might differ, so it used the same cost estimate for both. On the one hand, the IR-CPS canisters will have to deal with the added complexity of cold launch, but the canisters and missiles will be in the controlled environment of a submarine or ship. On the other hand, hot launch is less complex, but the LRHW canisters will need to be hardened to protect the missiles during travel on rough roads in all types of weather.

CBO's estimate of the procurement cost per missile also includes costs for assembling and integrating the missile's components and for testing to ensure that the components are not defective and that the assembly and integration have been done correctly. Testing is important for systems like the LRHW/IP-CPS, whose complexity is on a par with that of systems that launch satellites into space. For its estimate, CBO used information about assembly, integration, and testing costs provided by the Navy.

Table C-1.

Estimated Average Procurement Cost per Missile for an LRHW/IR-CPS

Millions of 2023 Dollars

	For First Missile (T-1)	Over Total Purchase of 300 Missiles
Booster and Missile Body	28.1	14.0
Glide Body	38.5	19.2
Canister	2.1	1.0
Missile Assembly, Integration, and Testing	12.8	6.4
Total for All-Up Round^a	81.3	40.7

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

CBO estimated values for each component on the basis of similar programs. Items such as the glide body and nose cone were scaled by the estimated size of the component as shown in images released by the Department of Defense. A 90 percent learning curve (in which the per-missile cost declines by 10 percent every time the number produced has doubled) was applied to the estimated procurement quantities.

IR-CPS = Intermediate-Range Conventional Prompt Strike missile (being developed by the Navy); LRHW = Long-Range Hypersonic Weapon (being developed by the Army).

a. An all-up round, or AUR, is a fully assembled missile as delivered to its launch site.

Under the assumptions described above, CBO estimated that the procurement cost for the first LRHW/IR-CPS missile and canister (T-1) would amount to \$81 million (see Table C-1). Averaged over a total purchase of 300 missiles, the procurement cost per missile would decline to \$41 million, CBO estimates.¹ For that and the other estimates of procurement costs in this analysis, CBO applied a learning curve of 90 percent, meaning that the per-missile cost declines by 10 percent each time the number of missiles produced has doubled.

Platform and Platform Integration Costs

CBO’s estimates of the costs of integrating LRHW/IR-CPS missiles onto their launch platforms are based on the platforms suggested in the services’ current plans. The estimates do not include the costs of building launch platforms, such as submarines or ships, that are already in the force or that are planned to enter the force. However, CBO’s estimates do include the costs

of launcher equipment peculiar to the LRHW/IR-CPS system and other costs associated directly with integrating the missiles onto their launch platforms, including a portion of the fire control systems and software used to communicate target information to the missile system (though not the services’ broader command-and-control infrastructure).

The Army plans to launch LRHW missiles from M870 trailers towed by Oshkosh M983A4 tractor trucks, the same family of vehicles that tow current Patriot surface-to-air missile launchers. The Army has indicated that it plans to field six LRHW batteries. Each battery will have four launchers (which will carry two missiles apiece), a truck-mounted battery-operations center, and various support vehicles.

The Army has requested \$144 million of research, development, test, and evaluation funding for ground service equipment for the LRHW from 2023 to 2025. Using its previous analysis of options for fielding long-range ground-launched missiles, CBO estimates that purchasing new ground equipment for the five remaining LRHW batteries would cost about \$200 million, or \$40 million per battery.² Those costs might be lower if the Army could modify some existing equipment for use in LRHW batteries.

The Navy plans to launch IR-CPS missiles from Zumwalt class guided missile destroyers and later from new Virginia class attack submarines equipped with the Virginia payload module (VPM). In estimating platform costs for the IR-CPS system, CBO used the Navy’s estimate of \$900 million to replace the 155 millimeter guns on the three existing Zumwalt class destroyers with four vertical launch tubes per ship. CBO did not include the cost of VPM launchers in its estimate because the Navy already planned to install those launchers—beginning with the Block V variant of Virginia class submarines—to replace missile capacity that will be lost when the Navy’s four Ohio class guided missile submarines are retired. The VPM on a Block V Virginia class submarine will include four vertical launch tubes.

Each Zumwalt and VPM launch tube will be able to accommodate three IR-CPS missiles, although the Navy may opt to load some of the tubes with different

1. DoD reportedly plans to buy 306 LRHW/IR-CPS missiles (66 for the Army and 240 for the Navy). But for ease of comparing the options described in Chapter 4, CBO estimated the costs of a total procurement of 300 missiles in each option.

2. See Congressional Budget Office, *Options for Fielding Ground-Launched Long-Range Missiles* (February 2020), www.cbo.gov/publication/56068.



weapons. IR-CPS canisters will not be directly mounted in the Zumwalt or VPM tubes. Rather, the three IR-CPS missiles will be contained in an advanced payload module (APM) that will be mounted in the destroyers' and submarines' tubes.

The Navy received nearly \$900 million for IR-CPS platform integration from 2019 to 2022 and requested \$364 million for 2023. CBO assumed that platform integration costs would continue at the average annual amount provided during the 2019–2022 period until 2028, when the missiles are due to be fielded on Block V submarines, for a total of \$1.0 billion from 2024 to 2028.

CBO estimated an additional cost of \$1.2 billion to procure 58 APMs and associated shipboard systems. CBO based its estimate for an APM and combat system on the cost of the launcher that the Navy purchased to convert tubes for Trident ballistic missiles into launchers for Tomahawk cruise missiles, with an adjustment to that cost to account for the greater size of IR-CPS missiles. The 58 APMs would be enough for a full load of IR-CPS missiles on the Navy's 3 Zumwalt class destroyers (36 missiles in 12 launch tubes) and 11 submarines with Virginia payload modules (132 missiles in 44 launch tubes), with two spare APMs left over. In practice, however, the Zumwalt and Virginia launch tubes would probably not all carry APMs with IR-CPS missiles.

Sustainment, Support, and Other Costs

The last category of costs that CBO estimated for the missile systems in this analysis is costs to keep the missiles in the military's inventory for 20 years. Those costs cover such activities as maintaining the missiles (including repair and overhaul as they age); modifying, improving, and replacing outdated components; maintaining the facilities that handle the missiles; and other costs. Annual sustainment and support costs can vary widely, from a few thousand dollars per missile for newer, smaller systems to nearly \$3 million per missile for older, larger systems, such as Trident nuclear ballistic missiles.

CBO estimates that annual sustainment costs for LRHW/IR-CPS missiles would total about \$0.5 million per missile. That estimate is based on the maintenance portion of sustainment costs for Trident missiles, as estimated by DoD. CBO did not base its estimate on the full sustainment costs for Trident missiles because those missiles are much older (they have been deployed for

more than 30 years) and carry nuclear warheads—two factors that can substantially increase support costs.

The services could incur additional costs if they needed to establish new units and increase the number of personnel in each service to operate the LRHW/IR-CPS missiles. For example, on the basis of its earlier analysis of options for fielding long-range ground-launched missiles, CBO estimates that operation and support costs for an LRHW battery would total about \$25 million per year, including costs for military personnel.³ The Army would avoid that marginal cost if it converted existing units into LRHW batteries. The Navy, for its part, does not plan to purchase additional ships or submarines to accommodate IR-CPS missiles.

Costs of Hypersonic Boost-Glide Missiles for the Air Force

LRHW/IR-CPS missiles might be able to be launched from the cargo bay of a large transport aircraft, but the Air Force prefers to use bomber and fighter aircraft to launch strike missiles.⁴ Thus, the Air Force is developing a smaller hypersonic boost-glide missile, the AGM-183A ARRW, which is expected to have a much shorter range and a smaller warhead than the LRHW/IR-CPS missile. In the Air Force's plans, ARRW missiles will be launched from under the wings of B-52 bombers, but they may eventually be carried by other bombers or by large fighters, such as the F-15E or F-15EX. The potential ability of aircraft to get closer to their targets than surface launchers reduces the disadvantage of having missiles with a shorter range.

Procurement Costs

To estimate the procurement costs of an ARRW missile, CBO used an approach similar to the one it used for the LRHW/IR-CPS. The ARRW's single-stage booster has been described as a modified version of the booster used on the MGM-140 Army Tactical Missile System (ATACMS). Thus, CBO based the cost of the ARRW booster and missile body on actual costs for the ATACMS, scaled to account for the ARRW's significantly longer length and slightly larger diameter.

3. Ibid.

4. In 1974, the Air Force demonstrated the ability to launch a Minuteman intercontinental ballistic missile from the cargo bay of a C-5A transport plane, but the service did not end up pursuing that operational capability.

Table C-2.

Estimated Average Procurement Cost per Missile for an ARRW

Millions of 2023 Dollars

	For First Missile (T-1)	Over Total Purchase of 100 Missiles	Over Total Purchase of 300 Missiles
Booster and Missile Body	8.1	4.8	4.0
Glide Body	15.9	9.4	7.9
Shipping Container	0.5	0.5	0.5
Missile Assembly, Integration, and Testing	3.0	2.7	2.3
Total for All-Up Round^a	27.5	17.5	14.9

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

CBO estimated values for each component on the basis of similar programs. Items such as the glide body and nose cone were scaled by the estimated size of the component as shown in images released by the Department of Defense. A 90 percent learning curve (in which the per-missile cost declines by 10 percent every time the number produced has doubled) was applied to the estimated procurement quantities.

ARRW = Air-Launched Rapid Response Weapon (being developed by the Air Force).

a. An all-up round, or AUR, is a fully assembled missile as delivered to its launch site.

For the glide body, CBO adjusted its estimate for the Common Hypersonic Glide Body used in the LRHW/IR-CPS to account for the ARRW’s smaller size and the smaller amount of thermal protection that will be necessary because the ARRW will glide for a shorter distance in the atmosphere.

For costs to assemble and integrate the ARRW’s components, CBO scaled its estimate for the LRHW/IR-CPS to account for differences in the costs of the missiles’ physical components and their relative complexity. (For example, the LRHW/IR-CPS uses a two-stage booster, and the ARRW uses a single-stage booster.)

Those adjustments result in an average procurement cost of \$15 million per missile for a purchase of 300 missiles, CBO estimates (see Table C-2). The Air Force has not indicated how many ARRW missiles it plans to purchase, so for comparison purposes, CBO used the same procurement quantity as for the LRHW/IR-CPS. Accounting for testing and spare missiles, 300 ARRWs would allow for more than 65 B-52 missions with four missiles each. Alternatively, the Air Force may choose to

procure fewer missiles. If it purchased 100 missiles, for example, the average procurement cost per missile would increase to \$18 million.

By comparison, in its 2022 budget, the Air Force requested \$161 million to procure “an estimated 12 missiles,” implying a cost per missile of about \$13 million. In CBO’s estimates, procurement costs for the first 12 missiles average \$18 million each, about one-third more than the Air Force’s budget request. That difference reflects uncertainty about the physical and performance characteristics of ARRW missiles, which underlie CBO’s bottom-up estimate, as well as uncertainty about the number of missiles the Air Force could have actually acquired for \$161 million. (Several test failures have caused initial procurement funding for ARRW missiles to be delayed until after 2023, a change that is likely to add to the program’s cost.)

Platform and Platform Integration Costs

The Air Force has not indicated a need to buy additional aircraft to accommodate ARRW missiles. B-52s are being used as launch platforms in the ARRW test program, so CBO assumed that most costs to integrate the missiles onto those aircraft would be covered by development and testing funds. However, CBO estimates that fully integrating ARRWs into the combat system of operational B-52s would cost the Air Force an additional \$200 million.

Further costs would be incurred if the Air Force opted to integrate ARRW missiles onto its other bombers or the F-15E/EX. In particular, it can be more difficult to get safety authorization for a new weapon to be carried internally on aircraft such as the B-1, the B-2, or eventually the B-21 (as opposed to being carried under the wing on a B-52). CBO did not include those potential further costs in its estimates.

Sustainment, Support, and Other Costs

CBO estimates that sustaining and supporting the ARRW system would cost about \$0.1 million per missile each year. That number is based on CBO’s estimate for the LRHW/IR-CPS system, scaled down to account for differences in the missiles’ assembly, integration, and testing costs. In its estimate of sustainment costs for the ARRW, CBO did not include additional operation and support costs or military construction costs to store and maintain an inventory of missiles. Although not zero, those costs are likely to be small relative to other parts of



Table C-3.

Estimated Average Procurement Cost per Missile for an Intermediate-Range, Ground- or Sea-Launched Ballistic Missile Equipped With a MaRV

Millions of 2023 Dollars

	For First Missile (T-1)	Over Total Purchase of 300 Missiles
Booster and Missile Body	26.0	13.0
Reentry Vehicle	15.5	7.7
Canister and Material Handling Equipment	2.1	1.0
Missile Assembly, Integration, and Testing	8.1	4.1
Total for All-Up Round^a	51.6	25.8

Data source: Congressional Budget Office. See www.cbo.gov/publication/58255#data.

CBO estimated values for each component on the basis of similar programs. A 90 percent learning curve (in which the per-missile cost declines by 10 percent every time the number produced has doubled) was applied to the estimated procurement quantities.

MaRV = maneuverable reentry vehicle.

a. An all-up round, or AUR, is a fully assembled missile as delivered to its launch site.

the ARRW program and relative to what the Air Force spends to maintain its inventory of other conventional strike weapons.

Costs of Intermediate-Range, Ground- or Sea-Launched Ballistic Missiles Equipped With MaRVs

As an alternative to the hypersonic boost-glide missiles that DoD is developing, CBO examined notional ballistic missiles that would use boosters similar to those of the LRHW/IR-CPS but would carry ballistic reentry vehicles rather than more sophisticated glide bodies. A purely ballistic reentry vehicle with a conventional (nonnuclear) warhead would not be accurate enough for many targets, so CBO's notional ballistic missile would be equipped with a maneuverable reentry vehicle (MaRV). Maneuverable reentry vehicles have been studied since the 1960s and were deployed on the United States' intermediate-range Pershing II nuclear-armed missiles in the 1980s.

Procurement Costs

To estimate the procurement cost of an intermediate-range, ground- or sea-launched ballistic missile, CBO

started with its estimate for the LRHW/IR-CPS and substituted the cost of a MaRV for the cost of those missiles' hypersonic glide body. CBO based the cost of a MaRV on the Navy's estimates of the cost of the Conventional Trident Modification reentry vehicle proposed in 2006, adjusted by a growth factor representing cost growth in past missile programs.⁵

Those adjustments result in an average procurement cost of \$26 million per missile for a purchase of 300 ground- or sea-launched ballistic missiles equipped with MaRVs, CBO estimates (see Table C-3). That figure is 37 percent less than CBO's estimate of the cost to procure an LRHW/IR-CPS hypersonic boost-glide missile with the same range.

Platform and Platform Integration Costs

In CBO's estimation, platform integration costs would be roughly the same for the intermediate-range ballistic missiles as for the LRHW/IR-CPS missiles.

Sustainment, Support, and Other Costs

In CBO's estimation, sustainment costs would be roughly the same for the ballistic missile system as for the LRHW/IR-CPS systems.

Costs of Standard Missile-6 Block IB Missiles

The Navy's effort to develop a Block IB variant of the SM-6 short-range ballistic missile is relatively recent, and the exact specifications of the missile are still being worked out. Production of Standard missiles is long established, and the Navy has had success modifying the missiles for different purposes. Compared with most earlier variants of Standard missiles, the Block IB will use a larger-diameter (21-inch) rocket motor to achieve longer range and higher speed. Standard missiles have primarily been used on the Navy's surface combat ships, but air-launched versions have been used in the past. Modifications would be necessary to launch the missiles from submarines. In addition, the Army is considering purchasing the SM-6 for ground launch.

Procurement Costs

To provide a direct comparison with the other weapon systems, CBO assumed that the Army and the Navy

5. For a description of CBO's approach to analyzing growth in acquisition costs, see Congressional Budget Office, *An Analysis of the Obama Administration's Final Future Years Defense Program* (April 2017), pp. 47–50, www.cbo.gov/publication/52450.

would purchase a combined total of 300 Block IB missiles. On the basis of information provided by the Navy, CBO estimates that 300 missiles would have an average procurement cost of \$6 million per missile (including the canister). Production quantities for the Block IB could be larger if the Navy deployed the missile on more surface combatants than the three Zumwalt class destroyers planned for the IR-CPS and if the Army purchased Block IBs to equip its Mid-Range Capability (MRC) batteries. (Current plans call for MRC batteries to be equipped with SM-6 missiles and Tomahawk cruise missiles.)

Platform and Platform Integration Costs

CBO estimates about \$1 billion for platform and platform integration costs, including the same number

of launchers (58) as for the Navy's IR-CPS and ground equipment for six Army batteries. Costs would be lower than for the IR-CPS for two reasons. First, there would be no need to modify destroyers to use the Block IB missile; it would be compatible with those ships' existing MK 41 vertical launchers. And second, the launchers to be used in submarines' Virginia payload module tubes would be smaller (and less expensive) than the advanced payload module used to fire the IR-CPS missile. CBO's estimates do not include the costs of building launch platforms, such as submarines or ships, that are already in the force or that are planned to enter the force.

Sustainment, Support, and Other Costs

In CBO's estimation, sustainment costs would be roughly the same for the SM-6 missile as for the ARRW.

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About This Document

This report was prepared at the request of the Ranking Member of the Senate Committee on Armed Services. In keeping with the Congressional Budget Office's mandate to provide objective, impartial analysis, the report makes no recommendations.

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CBO seeks feedback to make its work as useful as possible. Please send comments to communications@cbo.gov.



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