Hypersonic Weapons: Background and Issues for Congress

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The United States has actively pursued the development of hypersonic weapons—maneuvering weapons that fly at speeds of at least Mach 5—as a part of its conventional prompt global strike program since the early 2000s. In recent years, the United States has focused such efforts on developing hypersonic glide vehicles, which are launched from a rocket before gliding to a target, and hypersonic cruise missiles, which are powered by high-speed, air-breathing engines during flight. As Vice Chairman of the Joint Chiefs of Staff and former Commander of U.S. Strategic Command General John Hyten has stated, these weapons could enable “responsive, long-range, strike options against distant, defended, and/or time-critical threats [such as road-mobile missiles] when other forces are unavailable, denied access, or not preferred.” Critics, on the other hand, contend that hypersonic weapons lack defined mission requirements, contribute little to U.S. military capability, and are unnecessary for deterrence.

Funding for hypersonic weapons has been relatively restrained in the past; however, both the Pentagon and Congress have shown a growing interest in pursuing the development and near-term deployment of hypersonic systems. This is due, in part, to the advances in these technologies in Russia and China, both of which have a number of hypersonic weapons programs and have likely fielded operational hypersonic glide vehicles—potentially armed with nuclear warheads. Most U.S. hypersonic weapons, in contrast to those in Russia and China, are not being designed for use with a nuclear warhead. As a result, U.S. hypersonic weapons will likely require greater accuracy and will be more technically challenging to develop than nuclear-armed Chinese and Russian systems.

The Pentagon’s FY2022 budget request for hypersonic research is $3.8 billion—up from $3.2 billion in the FY2021 request. The Missile Defense Agency additionally requested $247.9 million for hypersonic defense. At present, the Department of Defense (DOD) has not established any programs of record for hypersonic weapons, suggesting that it may not have approved either mission requirements for the systems or long-term funding plans. Indeed, as Principal Director for Hypersonics (Office of the Under Secretary of Defense for Research and Engineering) Mike White has stated, DOD has not yet made a decision to acquire hypersonic weapons and is instead developing prototypes to assist in the evaluation of potential weapon system concepts and mission sets.

As Congress reviews the Pentagon’s plans for U.S. hypersonic weapons programs, it might consider questions about the rationale for hypersonic weapons, their expected costs, and their implications for strategic stability and arms control. Potential questions include the following:

- What mission(s) will hypersonic weapons be used for? Are hypersonic weapons the most cost-effective means of executing these potential missions? How will they be incorporated into joint operational doctrine and concepts?
- Given the lack of defined mission requirements for hypersonic weapons, how should Congress evaluate funding requests for hypersonic weapons programs or the balance of funding requests for hypersonic weapons programs, enabling technologies, and supporting test infrastructure? Is an acceleration of research on hypersonic weapons, enabling technologies, or hypersonic missile defense options both necessary and technologically feasible?
- How, if at all, will the fielding of hypersonic weapons affect strategic stability?
- Is there a need for risk-mitigation measures, such as expanding New START, negotiating new multilateral arms control agreements, or undertaking transparency and confidence-building activities?
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Introduction

The United States has actively pursued the development of hypersonic weapons as a part of its conventional prompt global strike (CPGS) program since the early 2000s. In recent years, it has focused such efforts on hypersonic glide vehicles and hypersonic cruise missiles with shorter and intermediate ranges for use in regional conflicts. Although funding for these programs has been relatively restrained in the past, both the Pentagon and Congress have shown a growing interest in pursuing the development and near-term deployment of hypersonic systems. This is due, in part, to advances in these technologies in Russia and China, leading to a heightened focus in the United States on the strategic threat posed by hypersonic flight. Open-source reporting indicates that both China and Russia have conducted numerous successful tests of hypersonic glide vehicles and likely fielded an operational capability.

Experts disagree on the potential impact of competitor hypersonic weapons on both strategic stability and the U.S. military’s competitive advantage. Nevertheless, former Under Secretary of Defense for Research and Engineering (USD[R&E]) Michael Griffin has testified to Congress that the United States does not “have systems which can hold [China and Russia] at risk in a corresponding manner, and we don’t have defenses against [their] systems.” Although the John S. McCain National Defense Authorization Act for Fiscal Year 2019 (FY2019 NDAA, P.L. 115-232) accelerated the development of hypersonic weapons, which USD(R&E) identifies as a priority research and development area, the United States is unlikely to field an operational system before 2023. However, most U.S. hypersonic weapons programs, in contrast to those in Russia and China, are not being designed for use with a nuclear warhead. As a result, U.S. hypersonic weapons will likely require greater accuracy and will be more technically challenging to develop than nuclear-armed Chinese and Russian systems.

In addition to accelerating development of hypersonic weapons, Section 247 of the FY2019 NDAA required that the Secretary of Defense, in coordination with the Director of the Defense Intelligence Agency, produce a classified assessment of U.S. and adversary hypersonic weapons programs, to include the following elements:

1. An evaluation of spending by the United States and adversaries on such technology.
2. An evaluation of the quantity and quality of research on such technology.
3. An evaluation of the test infrastructure and workforce supporting such technology.
4. An assessment of the technological progress of the United States and adversaries on such technology.
5. Descriptions of timelines for operational deployment of such technology.

1 For details, see CRS Report R41464, Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues, by Amy F. Woolf.
3 Until recently, the United States was not believed to be considering the development of nuclear-armed hypersonic weapons; however, a since-revoked Air Force solicitation sought ideas for a “thermal protection system that can support [a] hypersonic glide to ICBM ranges.” Senior defense officials responded to news reports of the revocation, stating that DOD “remains committed to non-nuclear role for hypersonics.” See Steve Trimble, “USAF Errantly Reveals Research on ICBM-Range Hypersonic Glide Vehicle,” Aviation Week, August 18, 2020, https://aviationweek.comdefense-space/missile-defense-weapons/usaf-errantly-reveals-research-icbm-range-hypersonic-glide.
(6) An assessment of the intent or willingness of adversaries to use such technology.\textsuperscript{4}

This report was delivered to Congress in July 2019. Similarly, Section 1689 of the FY2019 NDAA requires the Director of the Missile Defense Agency to produce a report on “how hypersonic missile defense can be accelerated to meet emerging hypersonic threats.”\textsuperscript{5} The findings of these reports could hold implications for congressional authorizations, appropriations, and oversight.

The following report reviews the hypersonic weapons programs in the United States, Russia, and China, providing information on the programs and infrastructure in each nation, based on unclassified sources. It also provides a brief summary of the state of global hypersonic weapons research development. It concludes with a discussion of the issues that Congress might address as it considers DOD’s funding requests for U.S. hypersonic technology programs.

**Background**

Several countries are developing hypersonic weapons, which fly at speeds of at least Mach 5 (five times the speed of sound).\textsuperscript{6} There are two primary categories of hypersonic weapons:

- **Hypersonic glide vehicles (HGV)** are launched from a rocket before gliding to a target.\textsuperscript{7}
- **Hypersonic cruise missiles** are powered by high-speed, air-breathing engines, or “scramjets,” after acquiring their target.

Unlike ballistic missiles, hypersonic weapons do not follow a ballistic trajectory and can maneuver en route to their destination. As Vice Chairman of the Joint Chiefs of Staff and former Commander of U.S. Strategic Command General John Hyten has stated, hypersonic weapons could enable “responsive, long-range, strike options against distant, defended, and/or time-critical threats [such as road-mobile missiles] when other forces are unavailable, denied access, or not preferred.”\textsuperscript{8} Conventional hypersonic weapons use only kinetic energy—energy derived from motion—to destroy unhardened targets or, potentially, underground facilities.\textsuperscript{9}

Hypersonic weapons could challenge detection and defense due to their speed, maneuverability, and low altitude of flight.\textsuperscript{10} For example, terrestrial-based radar cannot detect hypersonic weapons until late in the weapon’s flight.\textsuperscript{11} Figure 1 depicts the differences in terrestrial-based radar detection timelines for ballistic missiles versus hypersonic glide vehicles.

\begin{itemize}
  \item \textsuperscript{4}P.L. 115-232, Section 2, Division A, Title II, §247.
  \item \textsuperscript{5}P.L. 115-232, Section 2, Division A, Title XVI, §1689.
  \item \textsuperscript{6}At a minimum, the United States, Russia, China, Australia, India, France, Germany, and Japan are developing hypersonic weapons technology. See Richard H. Speier et al., Hypersonic Missile Proliferation: Hindering the Spread of a New Class of Weapons, RAND Corporation, 2017, https://www.rand.org/pubs/research_reports/RR2137.html; and Mike Yeo, “Japan unveils its hypersonic weapons plans,” Defense News, March 14, 2020.
  \item \textsuperscript{7}When HGVs are mated with their rocket booster, the resulting weapon system is often referred to as a hypersonic boost-glide weapon.
  \item \textsuperscript{9}Richard H. Speier et al., Hypersonic Missile Proliferation: Hindering the Spread of a New Class of Weapons, p. 13.
  \item \textsuperscript{11}Richard H. Speier et al., Hypersonic Missile Proliferation: Hindering the Spread of a New Class of Weapons.
This delayed detection compresses the timeline for decisionmakers assessing their response options and for a defensive system to intercept the attacking weapon—potentially permitting only a single intercept attempt.\(^\text{12}\)

Furthermore, U.S. defense officials have stated that both terrestrial- and current space-based sensor architectures are insufficient to detect and track hypersonic weapons, with former USD(R&E) Griffin noting that “hypersonic targets are 10 to 20 times dimmer than what the U.S. normally tracks by satellites in geostationary orbit.”\(^\text{13}\) Some analysts have suggested that space-based sensor layers—integrated with tracking and fire-control systems to direct high-performance interceptors or directed energy weapons—could theoretically present viable options for defending against hypersonic weapons in the future.\(^\text{14}\) Indeed, the 2019 Missile Defense Review notes that “such sensors take advantage of the large area viewable from space for improved tracking and potentially targeting of advanced threats, including HGVs and hypersonic cruise missiles.”\(^\text{15}\)

Other analysts have questioned the affordability, technological feasibility, and/or utility of wide-area hypersonic weapons defense.\(^\text{16}\) As physicist and nuclear expert James Acton explains, “point-defense systems, and particularly [Terminal High-Altitude Area Defense (THAAD)], could very plausibly be adapted to deal with hypersonic missiles. The disadvantage of those systems is that they can only defend small areas. To defend the whole of the continental United States, you

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\(^{14}\) “Testimony of Michael Griffin”; and “Testimony of John E. Hyten.”


would need an unaffordable number of THAAD batteries.”

In addition, some analysts have argued that the United States’ current command and control architecture would be incapable of “processing data quickly enough to respond to and neutralize an incoming hypersonic threat.”

(For additional information on hypersonic missile defense, see CRS In Focus IF11623, Hypersonic Missile Defense: Issues for Congress, by Kelley M. Sayler and Stephen M. McCall.)

### United States

The Department of Defense (DOD) is currently developing hypersonic weapons under the Navy’s Conventional Prompt Strike program, which is intended to provide the U.S. military with the ability to strike hardened or time-sensitive targets with conventional warheads, as well as through several Air Force, Army, and DARPA programs. Those who support these development efforts argue that hypersonic weapons could enhance deterrence, as well as provide the U.S. military with an ability to defeat capabilities such as advanced air and missile defense systems that form the foundation of U.S. competitors’ anti-access/area denial strategies. In recognition of this, the 2018 National Defense Strategy identifies hypersonic weapons as one of the key technologies “[ensuring the United States] will be able to fight and win the wars of the future.” Similarly, the House Armed Services Committee’s bipartisan Future of Defense Task Force Report notes that hypersonic weapons could present challenges to the United States in the years to come.

### Programs

Unlike programs in China and Russia, U.S. hypersonic weapons are to be conventionally armed. As a result, U.S. hypersonic weapons will likely require greater accuracy and will be more technically challenging to develop than nuclear-armed Chinese and Russian systems. Indeed, according to one expert, “a nuclear-armed glider would be effective if it were 10 or even 100 times less accurate [than a conventionally-armed glider]” due to nuclear blast effects.

According to open-source reporting, the United States is conducting research, development, test, and evaluation (RDT&E) on a number of offensive hypersonic weapons and hypersonic technology programs, including the following (see Table 1):

17 Acton, “Hypersonic Weapons Explainer.”
19 For a full history of U.S. hypersonic weapons programs, see CRS Report R41464, Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues, by Amy F. Woolf.
• U.S. Navy—Conventional Prompt Strike (CPS);
• U.S. Army—Long-Range Hypersonic Weapon (LRHW);
• U.S. Air Force—AGM-183 Air-Launched Rapid Response Weapon (ARRW, pronounced “arrow”);
• U.S. Air Force—Hypersonic Attack Cruise Missile (HACM);
• DARPA—Tactical Boost Glide (TBG);
• DARPA—Operational Fires (OpFires); and
• DARPA—Hypersonic Air-breathing Weapon Concept (HAWC, pronounced “hawk”).

These programs are intended to produce operational prototypes, as there are currently no programs of record for hypersonic weapons. 24

**U.S. Navy**

In a June 2018 memorandum, DOD announced that the Navy would lead the development of a common glide vehicle for use across the services. 25 The common glide vehicle is being adapted from a Mach 6 Army prototype warhead, the Alternate Re-Entry System, which was successfully tested in 2011 and 2017. 26 Once development is complete, “Sandia National Laboratories, the designer of the original concept, then will build the common glide vehicles... Booster systems are being developed separately.” 27

The Navy’s Conventional Prompt Strike (CPS) is expected to pair the common glide vehicle with a booster system to create a common All Up Round (AUR) for use by both the Navy and Army. According to the Navy’s FY2022 budget documents, the Navy intends to conduct testing in support of CPS’s deployment on Zumwalt-class destroyers by FY2025 and Virginia-class submarines by FY2028. 28 Although Navy officials have previously noted plans to achieve “limited operating capability” on Ohio-class submarines as early as 2025 29 and to eventually field hypersonic weapons on Burke-class destroyers, such plans are not reflected in FY2022 budget

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documents. The Navy is requesting $1.4 billion for CPS RDT&E in FY2022—an increase of $366 million over the FY2021 request and $607 million over the FY2021 appropriation.

U.S. Army

The Army’s Long-Range Hypersonic Weapon program is expected to pair the common glide vehicle with the Navy’s booster system. The system is intended to have a range of over 1,725 miles and “provide the Army with a prototype strategic attack weapon system to defeat A2/AD capabilities, suppress adversary Long Range Fires, and engage other high payoff/time sensitive targets.” The Army is requesting $301 million in RDT&E for the program in FY2022—$500 million under the FY2021 request and $531 million under the FY2021 appropriation. It plans to conduct flight tests for LRHW in FY2022 and FY2023, field an experimental prototype in FY2023, and transition to a program of record in the fourth quarter of FY2024.

U.S. Air Force

The AGM-183 Air-Launched Rapid Response Weapon is expected to leverage DARPA’s Tactical Boost Glide technology to develop an air-launched hypersonic glide vehicle prototype capable of travelling at average speeds of between Mach 6.5 and Mach 8 at a range of approximately 1,000 miles. Despite testing delays due to technical challenges, ARRW successfully completed a “captive carry” test flight in June 2019; its first free-flight test failed in April 2021. The Air Force has requested $238 million for ARRW RDT&E in FY2022—$144 million under the

FY2021 request and $148 million under the FY2021 appropriation. In addition, the Air Force has requested $161 million in FY2022 for the procurement of an estimated 12 ARRW missiles.

In February 2020, the Air Force announced that it had cancelled its second hypersonic weapon program, the Hypersonic Conventional Strike Weapon (HCSW), which had been expected to use the common glide vehicle and booster system, due to budget pressures that forced it to choose between ARRW and HCSW. Then-Air Force acquisition chief Will Roper explained that ARRW was selected because it was more advanced and gave the Air Force additional options. “[ARRW] is smaller; we can carry twice as many on the B-52, and it’s possible it could be on the F-15,” he explained. A senior Air Force official has since noted that a B-52 could potentially carry four ARRWs.

Finally, in FY2022, the Air Force launched the Hypersonic Attack Cruise Missile (HACM) program to develop a hypersonic cruise missile that integrates Air Force and DARPA technologies. Some reports indicate that HACM is intended to be launched from both bombers and fighter aircraft, with a senior Air Force official noting that a B-52 could potentially carry 20 HACMs or more. According to the Air Force, “the ability to execute HACM development is contingent upon fully funded and successful predecessor capability development efforts.” The Air Force requested $200 million for HACM in FY2022.

The Air Force is also seeking information from industry on the Expendable Hypersonic Air-Breathing Multi-Mission Demonstrator Program, alternatively known as Project Mayhem. According to Principal Director for Hypersonics Mike White, “Project Mayhem is to look at the next step in what the opportunity space allows relative to hypersonic cruise missile systems” and is intended to be capable of flying “significantly longer ranges than what we’re doing today.”

45 Mike White, Remarks at the Center for Strategic and International Studies, “Hypersonic Strike and Defense: A
Mayhem is reported to be larger than ARRW and capable of carrying multiple payloads for different mission sets.  

**DARPA**

DARPA, in partnership with the Air Force, continues to test Tactical Boost Glide, a wedge-shaped hypersonic glide vehicle capable of Mach 7+ flight that “aims to develop and demonstrate technologies to enable future air-launched, tactical-range hypersonic boost glide systems.”  

TBG will “also consider traceability, compatibility, and integration with the Navy Vertical Launch System” and is planned to transition to both the Air Force and the Navy. DARPA has requested $50 million for TBG in FY2022—$67 million under the FY2021 request and $32 million under the FY2021 appropriation.

DARPA’s Operational Fires reportedly seeks to leverage TBG technologies to develop a ground-launched system that will enable “advanced tactical weapons to penetrate modern enemy air defenses and rapidly and precisely engage critical time sensitive targets.” DARPA has requested $45 million for OpFires in FY2022—$5 million over the FY2021 request and $3 million under the FY2022 appropriation.

In the longer term, DARPA, with Air Force support, is continuing work on the Hypersonic Air-breathing Weapon Concept, which “seeks to develop and demonstrate critical technologies to enable an effective and affordable air-launched hypersonic cruise missile.” Principal Director for Hypersonics Mike White has stated that such a missile would be smaller than DOD’s hypersonic glide vehicles and could therefore launch from a wider range of platforms. Principal Director White has additionally noted that HAWC and other hypersonic cruise missiles could integrate seekers more easily than hypersonic glide vehicles. DARPA requested $10 million to develop HAWC in FY2022—$10 million under the FY2021 request and $21 million under the FY2021 appropriation.

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Table 1. Summary of U.S. Hypersonic Weapons RDT&E Funding

<table>
<thead>
<tr>
<th>Title</th>
<th>FY2021 Request ($ in millions)</th>
<th>FY2021 Enacted ($ in millions)</th>
<th>PB2022 ($ in millions)</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Prompt Strike (CPS)</td>
<td>1,008</td>
<td>767</td>
<td>1,374</td>
<td>Platform deployment in FY2025 and FY2028</td>
</tr>
<tr>
<td>Long-Range Hypersonic Weapon (LRHW)</td>
<td>801</td>
<td>832</td>
<td>301</td>
<td>Prototype deployment in FY2023</td>
</tr>
<tr>
<td>AGM-183 Air-Launched Rapid Response Weapon (ARRW)</td>
<td>382</td>
<td>386</td>
<td>238</td>
<td>Early operational capability in FY2022</td>
</tr>
<tr>
<td>Hypersonic Attack Cruise Missile (HACM)</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>Complete critical design review in FY2023</td>
</tr>
<tr>
<td>Tactical Boost Glide (TBG)</td>
<td>117</td>
<td>82</td>
<td>50</td>
<td>Continue tests in FY2022</td>
</tr>
<tr>
<td>Operational Fires (OpFires)</td>
<td>40</td>
<td>48</td>
<td>45</td>
<td>Complete critical design review in FY2022</td>
</tr>
<tr>
<td>Hypersonic Air-breathing Weapon Concept (HAWC)</td>
<td>20</td>
<td>31</td>
<td>10</td>
<td>Complete final program review in FY2022</td>
</tr>
</tbody>
</table>


**Hypersonic Missile Defenses**

DOD is also investing in counter-hypersonic weapons capabilities, although former USD(R&E) Michael Griffin has stated that the United States will not have a defensive capability against hypersonic weapons until the mid-2020s, at the earliest. In September 2018, the Missile Defense Agency (MDA)—which in 2017 established a Hypersonic Defense Program pursuant to Section 1687 of the FY2017 NDAA (P.L. 114-840)—commissioned 21 white papers to explore hypersonic missile defense options, including interceptor missiles, hypervelocity projectiles, laser guns, and electronic attack systems. In January 2020, MDA issued a draft request for prototype proposals for a Hypersonic Defense Regional Glide Phase Weapons System interceptor. This effort is intended to “reduce interceptor key technology and integration risks, anchor modeling and simulation in areas of large uncertainty, and to increase the interceptor technology readiness levels (TRL) to level 5” (validating components in a relevant environment). MDA has also

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53 For additional information about hypersonic missile defense, see CRS In Focus IF11623, *Hypersonic Missile Defense: Issues for Congress*, by Kelley M. Sayler, Stephen M. McCall, and Quintin A. Reed.


awarded four companies—Northrop Grumman, Raytheon, Leidos, and L3Harris—with $20 million contracts to design prototype space-based (low-Earth orbit) sensors by October 31, 2020.\footnote{Sandra Erwin, “Missile Defense Agency selects four companies to develop space sensors,” Space News, October 30, 2019, https://spacenews.com/mis sile-defense-agency-selects-four-companies-to-develop-space-sensors/.} Such sensors could theoretically extend the range at which incoming missiles could be detected and tracked—a critical requirement for hypersonic missile defense, according to then-USD(R&E) Griffin.\footnote{MDA requested $248 million for hypersonic defense in FY2022—up from its $207 million FY2021 request and down from the $273 million FY2021 appropriation.\footnote{In addition, DARPA is working on a program called Glide Breaker, which “will develop critical component technology to support a lightweight vehicle designed for precise engagement of hypersonic threats at very long range.” DARPA requested $7 million for Glide Breaker in FY2022, matching the $7 million appropriation in FY2021.}} In addition, DARPA is working on a program called Glide Breaker, which “will develop critical component technology to support a lightweight vehicle designed for precise engagement of hypersonic threats at very long range.” DARPA requested $7 million for Glide Breaker in FY2022, matching the $7 million appropriation in FY2021.\footnote{A more recent report by the Government Accountability Office states that there are “26 DOD, DOE, NASA, and private U.S. wind tunnel facilities capable of supporting hypersonic research.” Government Accountability Office, Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts, GAO-21-378, March 22, 2021, p. 15, https://www.gao.gov/products/gao-21-378.}  

### Infrastructure

According to a study mandated by the FY2013 National Defense Authorization Act (P.L. 112-239) and conducted by the Institute for Defense Analyses (IDA),\footnote{A more recent report by the Government Accountability Office states that there are “26 DOD, DOE, NASA, and private U.S. wind tunnel facilities capable of supporting hypersonic research.” Government Accountability Office, Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts, GAO-21-378, March 22, 2021, p. 15, https://www.gao.gov/products/gao-21-378.} the United States had 48 critical hypersonic test facilities and mobile assets in 2014 needed for the maturation of hypersonic technologies for defense systems development through 2030.\footnote{These conditions additionally require the development of specialized materials such as metals and ceramics.} These specialized facilities, which simulate the unique conditions experienced in hypersonic flight (e.g., speed, pressure, heating),\footnote{These conditions additionally require the development of specialized materials such as metals and ceramics.} included 10 DOD hypersonic ground test facilities, 11 DOD open-air ranges, 11 DOD mobile assets, 9 NASA facilities, 2 Department of Energy (DOE) facilities, and 5 industry or academic facilities.\footnote{This list is taken directly from a 2014 Institute for Defense Analysis report and, therefore, may not be current. See (U//FOUO) Paul F. Piscopo et al., (U) Study on the Ability of the U.S. Test and Evaluation Infrastructure to Effectively and Efficiently Mature Hypersonic Technologies for Defense Systems Development: Summary Analysis and Assessment, Institute for Defense Analyses, September 2014. Permission to use this material has been granted by the Office of Science and Technology Policy.} In its 2014 evaluation of U.S. hypersonic test and evaluation infrastructure, IDA noted that “no current U.S. facility can provide full-scale, time-dependent,
coupled aerodynamic and thermal-loading environments for flight durations necessary to evaluate these characteristics above Mach 8.”

Since the 2014 study report was published, there have been a number of changes in U.S. hypersonic test infrastructure. For example, the University of Notre Dame has opened a Mach 6 hypersonic wind tunnel and at least one hypersonic testing facility has been inactivated. Development of Mach 8 and Mach 10 wind tunnels at Purdue University and the University of Notre Dame, respectively, is ongoing. In addition, the University of Arizona modified one of its wind tunnels to enable Mach 5 testing, while Texas A&M University—in partnership with Army Futures Command—is constructing a kilometer-long Mach 10 wind tunnel. (For a partial list of U.S. hypersonic test assets and their capabilities, see the Appendix.) The United States also uses the Royal Australian Air Force Woomera Test Range in Australia and the Andøya Rocket Range in Norway for flight testing. In January 2019, the Navy announced plans to reactivate its Launch Test Complex at China Lake, CA to improve air launch and underwater testing capabilities for the conventional prompt strike program. According to an assessment conducted by the Government Accountability Office, DOD has dedicated approximately $1 billion to hypersonic facility modernization from FY2015 to FY2024.

In April 2020, DOD’s Office of Inspector General announced that it would be evaluating current ground test and evaluation facilities to determine if the capability and capacity would be sufficient to execute DOD’s planned test schedule. Similarly, Section 222 of the FY2021 NDAA (P.L. 116-283) requires the Under Secretary of Defense for Research and Engineering, in consultation with the Director of Operational Test and Evaluation, to submit to the congressional defense committees “an assessment of the sufficiency of the testing capabilities and infrastructure used for fielding hypersonic weapons, and a description of any investments in testing capabilities and infrastructure that may be required to support in-flight and ground-based testing for such weapons.”

In addition, in March 2020, DOD announced that it had established a “hypersonic war room” to assess the U.S. industrial base for hypersonic weapons and identify “critical nodes” in the supply


67 University of Arizona, “Mach 5 Quiet Ludwieg Tube,” https://transition.arizona.edu/facilities/qlt5?_ga=2.62515882.768526379.1582843192-983632914.1582843192; and Ashley Tressel, “Army to open hypersonic testing facility at Texas A&M,” Inside Defense, October 13, 2019, https://insidedefense.com/daily-news/army-open-hypersonic-testing-facility-texas-am. Additional universities such as the University of Maryland, the California Institute of Technology, the Georgia Institute of Technology, the Air Force Academy, the University of Tennessee, and Virginia Polytechnic Institute and State University also maintain experimental hypersonic facilities or conduct hypersonic research.

68 (U/FOUO) Paul F. Piscopo et al., (U) Study on the Ability of the U.S. Test and Evaluation Infrastructure.


chain. DOD has also amended its “5000 series” acquisition policy in order to enhance supply chain resiliency and reduce sustainment costs.

**Russia**

Although Russia has conducted research on hypersonic weapons technology since the 1980s, it accelerated its efforts in response to U.S. missile defense deployments in both the United States and Europe, and in response to the U.S. withdrawal from the Anti-Ballistic Missile Treaty in 2001. Detailing Russia’s concerns, President Putin stated that “the US is permitting constant, uncontrolled growth of the number of anti-ballistic missiles, improving their quality, and creating new missile launching areas. If we do not do something, eventually this will result in the complete devaluation of Russia’s nuclear potential. Meaning that all of our missiles could simply be intercepted.” Russia thus seeks hypersonic weapons, which can maneuver as they approach their targets, as an assured means of penetrating U.S. missile defenses and restoring its sense of strategic stability.

**Programs**

Russia is pursuing two hypersonic weapons programs—the Avangard and the 3M22 Tsirkon (or Zircon)—and has reportedly fielded the Kinzhal (“Dagger”), a maneuvering air-launched ballistic missile.

Avangard (Figure 2) is a hypersonic glide vehicle launched from an intercontinental ballistic missile (ICBM), giving it “effectively ‘unlimited’ range.” Reports indicate that Avangard is currently deployed on the SS-19 Stiletto ICBM, though Russia plans to eventually launch the vehicle from the Sarmat ICBM. Sarmat is still in development, although it is scheduled to be deployed by the end of 2022. Avangard features onboard countermeasures and will reportedly

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77 Although the Kinzhal is a maneuvering air-launched ballistic missile rather than a hypersonic glide vehicle or hypersonic cruise missile, it is often included in reporting of Russia’s hypersonic weapons program. For this reason—and because it poses defensive challenges that are similar to other hypersonic weapons—it is included here for reference.


carry a nuclear warhead. It was successfully tested twice in 2016 and once in December 2018, reportedly reaching speeds of Mach 20; however, an October 2017 test resulted in failure. Russian news sources claim that Avangard entered into combat duty in December 2019.80

Figure 2. Artist Rendering of Avangard

Source: https://janes.ihs.com/janes_Display/FG_899127-JIR.

In addition to Avangard, Russia is developing Tsirkon, a ship-launched hypersonic cruise missile capable of traveling at speeds of between Mach 6 and Mach 8. Tsirkon is reportedly capable of striking both ground and naval targets. According to Russian news sources, Tsirkon has a range of between approximately 250 and 600 miles and can be fired from the vertical launch systems mounted on cruisers Admiral Nakhimov and Pyotr Veliky, Project 20380 corvettes, Project 22350 frigates, and Project 885 Yasen-class submarines, among other platforms.81 These sources assert that Tsirkon was successfully launched from a Project 22350 frigate in January and October 2020.82 U.S. intelligence reports indicate that the missile will become operational in 2023.83

In addition, Russia has reportedly fielded Kinzhal, a maneuvering air-launched ballistic missile modified from the Iskander missile. According to U.S. intelligence reports, Kinzhal was successfully test fired from a modified MiG-31 fighter (NATO code name: Foxhound) in July 2018—striking a target at a distance of approximately 500 miles—and may now be ready for combat.84 Russia plans to deploy the missile on both the MiG-31 and the Su-34 long-range strike

80 “First regiment of Avangard hypersonic missile systems goes on combat duty in Russia,” TASS, December 27, 2019, https://tass.com/defense/1104297.
fighter.\textsuperscript{85} Russia is working to mount the missile on the Tu-22M3 strategic bomber (NATO code name: Backfire), although the slower-moving bomber may face challenges in "accelerating the weapon into the correct launch parameters."\textsuperscript{86}

Russian media has reported Kinzhal’s top speed as Mach 10, with a range of up to 1,200 miles when launched from the MiG-31. The Kinzhal is reportedly capable of maneuverable flight, as well as of striking both ground and naval targets, and could eventually be fitted with a nuclear warhead. However, such claims regarding Kinzhal’s performance characteristics have not been publicly verified by U.S. intelligence agencies, and have been met with skepticism by a number of analysts.\textsuperscript{87}

**Infrastructure**

Russia reportedly conducts hypersonic wind tunnel testing at the Central Aero-Hydrodynamic Institute in Zhukovsky and the Khristianovich Institute of Theoretical and Applied Mechanics in Novosibirsk, and has tested hypersonic weapons at Dombarovskiy Air Base, the Baykonur Cosmodrome, and the Kura Range.\textsuperscript{88}

**China**

According to Tong Zhao, a fellow at the Carnegie-Tsinghua Center for Global Policy, “most experts argue that the most important reason to prioritize hypersonic technology development [in China] is the necessity to counter specific security threats from increasingly sophisticated U.S. military technology,” such as U.S. regional missile defenses.\textsuperscript{89} In particular, China’s pursuit of hypersonic weapons, like Russia’s, reflects a concern that U.S. hypersonic weapons could enable the United States to conduct a preemptive, decapitating strike on China’s nuclear arsenal and supporting infrastructure. U.S. missile defense deployments could then limit China’s ability to conduct a retaliatory strike against the United States.\textsuperscript{90}

China has demonstrated a growing interest in Russian advances in hypersonic weapons technology, conducting flight tests of a hypersonic-glide vehicle (HGV) only days after Russia tested its own system.\textsuperscript{91} Furthermore, a January 2017 report found that over half of open-source

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\textsuperscript{89} Tong Zhao, “Conventional Challenges to Strategic Stability: Chinese Perceptions of Hypersonic Technology and the Security Dilemma.”


\textsuperscript{91} Lora Saalman, “China’s Calculus on Hypersonic Glide.”
Chinese papers on hypersonic weapons include references to Russian weapons programs. This could indicate that China is increasingly considering hypersonic weapons within a regional context. Indeed, some analysts believe that China may be planning to mate conventionally armed HGVs with the DF-21 and DF-26 ballistic missiles in support of an anti-access/area denial strategy. China has reportedly not made a final determination as to whether its hypersonic weapons will be nuclear- or conventionally-armed—or dual-capable.

**Programs**

China has conducted a number of successful tests of the DF-17, a medium-range ballistic missile specifically designed to launch HGVs. U.S. intelligence analysts assess that the missile has a range of approximately 1,000 to 1,500 miles and may now be deployed. China has also tested the DF-41 intercontinental ballistic missile, which could be modified to carry a conventional or nuclear HGV, according to a report by a U.S. Congressional commission. The development of the DF-41 thus “significantly increases the [Chinese] rocket force’s nuclear threat to the U.S. mainland,” the report states.

China has tested the DF-ZF HGV (previously referred to as the WU-14) at least nine times since 2014. U.S. defense officials have reportedly identified the range of the DF-ZF as approximately 1,200 miles and have stated that the vehicle may be capable of performing “extreme maneuvers” during flight. Although unconfirmed by intelligence agencies, some analysts believe the DF-ZF could have become operational as early as 2020.

According to U.S. defense officials, China also successfully tested Starry Sky-2 (or Xing Kong-2), a nuclear-capable hypersonic vehicle prototype, in August 2018. China claims the vehicle reached top speeds of Mach 6 and executed a series of in-flight maneuvers before landing. Unlike the DF-ZF, Starry Sky-2 is a “waverider” that uses powered flight after launch and derives

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lift from its own shockwaves. Some reports indicate that the Starry Sky-2 could be operational by 2025. U.S. officials have declined to comment on the program.

Infrastructure

China has a robust research and development infrastructure devoted to hypersonic weapons. Then-USD(R&E) Michael Griffin stated in March 2018 that China has conducted 20 times as many hypersonic tests as the United States. China tested three hypersonic vehicle models (D18-1S, D18-2S, and D18-3S)—each with different aerodynamic properties—in September 2018. Analysts believe that these tests could be designed to help China develop weapons that fly at variable speeds, including hypersonic speeds. Similarly, China has used the Lingyun Mach 6+ high-speed engine, or “scramjet,” test bed (Figure 3) to research thermal resistant components and hypersonic cruise missile technologies.

Figure 3. Lingyun-1 Hypersonic Cruise Missile Prototype

According to Jane’s Defence Weekly, “China is also investing heavily in hypersonic ground testing facilities.” For example, the China Aerodynamics Research and Development Center claims to have 18 wind tunnels, while the China Academy of Aerospace Aerodynamics is known to operate at least three hypersonic wind tunnels—the FD-02, FD-03, and FD-07—capable of reaching speeds of Mach 8, Mach 10, and Mach 12, respectively. China also operates the JF-12

103 Malcolm Claus and Andrew Tate, “Chinese hypersonic programme reflects regional priorities,” Jane’s (subscription required), March 12, 2019, https://janes.ihs.com/Janes/Display/FG_1731069-JIR.
106 Kelvin Wong, “China claims successful test of hypersonic waverider,” Jane’s (subscription required), August 10,
hypersonic wind tunnel, which reaches speeds of between Mach 5 and Mach 9 and the FD-21 hypersonic wind tunnel, which reaches speeds of between Mach 10 and Mach 15. It will reportedly complete construction of the JF-22 wind tunnel, capable of reaching speeds of Mach 30, in 2022. In addition, China is known to have tested hypersonic weapons at the Jiuquan Satellite Launch Center and the Taiyuan Satellite Launch Center.

Global Hypersonic Weapons Programs

Although the United States, Russia, and China possess the most advanced hypersonic weapons programs, a number of other countries—including Australia, India, France, Germany, and Japan—are also developing hypersonic weapons technology. Since 2007, the United States has collaborated with Australia on the Hypersonic International Flight Research Experimentation (HIFiRE) program to develop hypersonic technologies. The most recent HIFiRE test, successfully conducted in July 2017, explored the flight dynamics of a Mach 8 hypersonic glide vehicle, while previous tests explored scramjet engine technologies. HIFiRE’s successor, the Southern Cross Integrated Flight Research Experiment (SCIFiRE) program, is to further develop hypersonic air-breathing technologies. SCIFiRE demonstration tests are expected by the mid-2020s. In addition to the Woomera Test Range facilities—one of the largest weapons test facilities in the world—Australia reportedly operates seven hypersonic wind tunnels and is capable of testing speeds of up to Mach 30.

India has similarly collaborated with Russia on the development of BrahMos II, a Mach 7 hypersonic cruise missile. Although BrahMos II was initially intended to be fielded in 2017, news reports indicate that the program faces significant delays and is now scheduled to achieve initial operational capability between 2025 and 2028. Reportedly, India is also developing an indigenous, dual-capable hypersonic cruise missile as part of its Hypersonic Technology Demonstrator Vehicle program and successfully tested a Mach 6 scramjet in June 2019 and September 2020. India operates approximately 12 hypersonic wind tunnels and is capable of testing speeds of up to Mach 13.

France also has collaborated and contracted with Russia on the development of hypersonic technology. Although France has been investing in hypersonic technology research since the 1990s, it has only recently announced its intent to weaponize the technology. Under the V-max (Experimental Maneuvering Vehicle) program, France plans to modify its air-to-surface ASN4G supersonic missile for hypersonic flight by 2022. Some analysts believe that the V-max program is intended to provide France with a strategic nuclear weapon. France operates five hypersonic wind tunnels and is capable of testing speeds of up to Mach 21.

Germany successfully tested an experimental hypersonic glide vehicle (SHEFEX II) in 2012; however, reports indicate that Germany may have pulled funding for the program. German defense contractor DLR continues to research and test hypersonic vehicles as part of the European Union’s ATLLAS II project, which seeks to design a Mach 5-6 vehicle. Germany operates three hypersonic wind tunnels and is capable of testing speeds of up to Mach 11.

Finally, Japan is developing the Hypersonic Cruise Missile (HCM) and the Hyper Velocity Gliding Projectile (HVGP). According to Jane’s, Japan invested $122 million in HVGP in FY2019. It reportedly plans to field HVGPs for area suppression and neutralizing aircraft carriers. HVGP is expected to enter service in 2026, with a more advanced version available by 2030, while HCM is expected to enter service in 2030. The Japan Aerospace Exploration Agency operates three hypersonic wind tunnels, with two additional facilities at Mitsubishi Heavy Industries and the University of Tokyo.

Other countries—including Iran, Israel, and South Korea—have conducted foundational research on hypersonic airflows and propulsion systems, but may not be pursuing a hypersonic weapons capability at this time.

Note: For additional information about global hypersonic weapons programs, see Richard H. Speier et al., Hypersonic Missile Proliferation. For information about Japan’s hypersonic weapons research and development plans, see Mike Yeo, “Japan unveils its hypersonic weapons plans,” Defense News, March 14, 2020.
Issues for Congress

As Congress reviews the Pentagon’s plans for U.S. hypersonic weapons programs during the annual authorization and appropriations process, it might consider a number of questions about the rationale for hypersonic weapons, their expected costs, and their implications for strategic stability and arms control. This section provides an overview of some of these questions.

Mission Requirements

Although the Department of Defense is funding a number of hypersonic weapons programs, it has not established any programs of record, suggesting that it may not have approved requirements for hypersonic weapons or long-term funding plans. Indeed, as Principal Director for Hypersonics (USD[R&E]) Mike White has stated, DOD has not yet made a decision to acquire hypersonic weapons and is instead developing prototypes to “[identify] the most viable overarching weapon system concepts to choose from and then make a decision based on success and challenges.”

As Congress conducts oversight of U.S. hypersonic weapons programs, it may seek to obtain information about DOD’s evaluation of potential mission sets for hypersonic weapons, a cost analysis of alternative means of executing these mission sets, and an assessment of the enabling technologies—such as space-based sensors or autonomous command and control systems—that may be required to employ or defend against hypersonic weapons. For example, Section 1671 of the FY2021 NDAA (P.L. 116-283) directs the Chairman of the Joint Chiefs of Staff, in coordination with the Under Secretary of Defense for Policy, to submit to the congressional defense committees a report on strategic hypersonic weapons, including “a description of how the requirements for land and sea-based hypersonic weapons will be addressed with the Joint Requirements Oversight Council, and how such requirements will be formally provided to the military departments procuring such weapons.” This report is to additionally include “the potential target sets for hypersonic weapons ... and the required mission planning to support targeting by the United States Strategic Command and other combatant commands.”

Funding and Management Considerations

Principal Director for Hypersonics (USD[R&E]) Mike White has noted that DOD is prioritizing offensive programs while it determines “the path forward to get a robust defensive strategy.”

This approach is reflected in DOD’s recent budget requests. For example, DOD requested $247.9 million for hypersonic defense programs and $3.8 billion for hypersonic weapons programs in FY2022. Similarly, in FY2021, DOD requested $206.8 million for hypersonic defense programs and $3.2 billion for hypersonic weapons programs.

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109 Steve Trimble, “New Long-Term Pentagon Plan Boosts Hypersonics.”
110 Steve Trimble, “New Long-Term Pentagon Plan Boosts Hypersonics.”
Although the Defense Subcommittees of the Appropriations Committees increased FY2020 appropriations for both hypersonic offense and defense above the FY2020 request, they expressed concerns, noting in their joint explanatory statement of H.R. 1158 “that the rapid growth in hypersonic research has the potential to result in stove-piped, proprietary systems that duplicate capabilities and increase costs.”114 To mitigate this concern, they appropriated $100 million for DOD to establish a Joint Hypersonics Transition Office (JHTO) to “develop and implement an integrated science and technology roadmap for hypersonics” and “establish a university consortium for hypersonic research and workforce development” in support of DOD efforts.115

DOD established the JHTO in April 2020 and announced on October 26, 2020, that it awarded Texas A&M University with a $20 million contract—renewable for up to $100 million—to manage a University Consortium for Applied Hypersonics (UCAH).116 UCAH is to be overseen by a group of academic researchers from Texas A&M University, the Massachusetts Institute of Technology, the University of Minnesota, the University of Illinois at Urbana-Champaign, the University of Arizona, the University of Tennessee Space Institute, Morgan State University, the California Institute of Technology, Purdue University, the University of California-Los Angeles, and the Georgia Institute of Technology.117 The consortium is to “facilitate transitioning academic research into developing systems [as well as] work with the department to reduce system development timelines while maintaining quality control standards.”118

In addition, Section 1671 of the FY2021 NDAA (P.L. 116-283) directs the Secretary of the Army and the Secretary of the Navy to jointly submit to the congressional defense committees a report on LRHW and CPS, including total costs of the programs, “the strategy for such programs with respect to manning, training, and equipping, including cost estimates, [and] a testing strategy and schedule for such programs.” It directs the Director of Cost Assessment and Program Evaluation to submit to the congressional defense committees an independent cost estimate of these programs.119

Given the lack of defined mission requirements for hypersonic weapons, however, it may be challenging for Congress to evaluate the balance of funding for hypersonic weapons programs, enabling technologies, supporting test infrastructure, and hypersonic missile defense.

115 Ibid. The Joint Hypersonic Transition Office, then called the Joint Technology Office on Hypersonics, was originally mandated by Section 218 of the FY2007 NDAA (P.L. 109-364). The office was redesignated as the Joint Hypersonics Transition Office and given additional authorities in Section 214 of the FY2018 NDAA (P.L. 115-91). Section 216 of the FY2020 NDAA (P.L. 116-92) further amended the office’s authorities to include the ability to enter into agreements with institutions of higher learning. The office went unfunded until FY2020 and was not established until April 2020.
117 Ibid.
118 Ibid.
Strategic Stability

Analysts disagree about the strategic implications of hypersonic weapons. Some have identified two factors that could hold significant implications for strategic stability: the weapon’s short time-of-flight—which, in turn, compresses the timeline for response—and its unpredictable flight path—which could generate uncertainty about the weapon’s intended target and therefore heighten the risk of miscalculation or unintended escalation in the event of a conflict. This risk could be further compounded in countries that co-locate nuclear and conventional capabilities or facilities.

Some analysts argue that unintended escalation could occur as a result of warhead ambiguity, or from the inability to distinguish between a conventionally armed hypersonic weapon and a nuclear-armed one. However, as a United Nations report notes, “even if a State did know that an HGV launched toward it was conventionally armed, it may still view such a weapon as strategic in nature, regardless of how it was perceived by the State firing the weapon, and decide that a strategic response was warranted.”120 Differences in threat perception and escalation ladders could thus result in unintended escalation. Such concerns have previously led Congress to restrict funding for conventional prompt strike programs.121

Other analysts have argued that the strategic implications of hypersonic weapons are minimal. Pavel Podvig, a senior research fellow at the United Nations Institute for Disarmament Research, has noted that the weapons “don’t … change much in terms of strategic balance and military capability.”122 This, some analysts argue, is because U.S. competitors such as China and Russia already possess the ability to strike the United States with intercontinental ballistic missiles, which, when launched in salvos, could overwhelm U.S. missile defenses.123 Furthermore, these analysts note that in the case of hypersonic weapons, traditional principles of deterrence hold: “it is really a stretch to try to imagine any regime in the world that would be so suicidal that it would even think threatening to use—not to mention to actually use—hypersonic weapons against the United States … would end well.”124

Section 1671 of the FY2021 NDAA (P.L. 116-283) directs the Chairman of the Joint Chiefs of Staff, in coordination with the Under Secretary of Defense for Policy, to submit to the congressional defense committees a report that examines

How escalation risks will be addressed with regards to the use of strategic hypersonic weapons, including whether any risk escalation exercises have been conducted or are planned for the potential use of hypersonic weapons, and an analysis of the escalation risks posed by foreign hypersonic systems that are potentially nuclear and conventional dual-use capable weapons.


121 For a history of legislative activity on conventional prompt global strike, see CRS Report R41464, Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues, by Amy F. Woolf.


Arms Control

Some analysts who believe that hypersonic weapons could present a threat to strategic stability or inspire an arms race have argued that the United States should take measures to mitigate risks or limit the weapons’ proliferation. Proposed measures include expanding New START, negotiating new multilateral arms control agreements, and undertaking transparency and confidence-building measures.125

The New START Treaty, a strategic offensive arms treaty between the United States and Russia, does not currently cover weapons that fly on a ballistic trajectory for less than 50% of their flight, as do hypersonic glide vehicles and hypersonic cruise missiles.126 However, Article V of the treaty states that “when a Party believes that a new kind of strategic offensive arm is emerging, that Party shall have the right to raise the question of such a strategic offensive arm for consideration in the Bilateral Consultative Commission (BCC).” Accordingly, some legal experts hold that the United States could raise the issue in the BCC of negotiating to include hypersonic weapons in the New START limits.127 However, because New START is due to expire in 2026, this may be a short-term solution.128

As an alternative, some analysts have proposed negotiating a new international arms control agreement that would institute a moratorium or ban on hypersonic weapon testing. These analysts argue that a test ban would be a “highly verifiable” and “highly effective” means of preventing a potential arms race and preserving strategic stability.129 Other analysts have countered that a test ban would be infeasible, as “no clear technical distinction can be made between hypersonic missiles and other conventional capabilities that are less prompt, have shorter ranges, and also have the potential to undermine nuclear deterrence.”130 These analysts have instead proposed international transparency and confidence-building measures, such as exchanging weapons data; conducting joint technical studies; “providing advance notices of tests; choosing separate, distinctive launch locations for tests of hypersonic missiles; and placing restraints on sea-based tests.”131

125 See United Nations Office of Disarmament Affairs, Hypersonic Weapon; and Richard H. Speier et al., Hypersonic Missile Proliferation.
126 In some cases, hypersonic glide vehicles may be launched from intercontinental ballistic missiles that are already covered by New START, as is reported to be the case with Russia’s Avangard HGV. See Rachel S. Cohen, “Hypersonic Weapons: Strategic Asset or Tactical Tool?”
130 Tong Zhao, “Test Ban for Hypersonic Missiles?”
## Appendix. U.S. Hypersonic Testing Infrastructure

### Table A-1. DOD Hypersonic Ground Test Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capability</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Force Arnold Engineering and Development Complex (AEDC) von Karman</td>
<td>Tunnel A: 40-inch Mach 1.5-5.5; up to 290°F</td>
<td>Arnold AFB, TN</td>
</tr>
<tr>
<td>Gas Dynamics Facility Tunnels A/B/C</td>
<td>Tunnel B: 50-inch Mach 6 and 8; up to 900°F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tunnel C: 50-inch Mach 10; up to 1700 °F</td>
<td></td>
</tr>
<tr>
<td>Air Force AEDC High-Enthalpy Aerothermal Test Arc-Heated Facilities</td>
<td>Simulate thermal and pressure environments at speeds of up to Mach 8</td>
<td>Arnold AFB, TN</td>
</tr>
<tr>
<td>H1, H2, H3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Force AEDC Tunnel 9</td>
<td>59-inch Mach 7, 8,10, 14, and 18; up to 2900 °F</td>
<td>White Oak, MD</td>
</tr>
<tr>
<td>Air Force AEDC Aerodynamic and Propulsion Test Unit</td>
<td>Mach 3.1-7.2; up to 1300 °F</td>
<td>Arnold AFB, TN</td>
</tr>
<tr>
<td>Air Force AEDC Aeroballistic Range G</td>
<td>Launches projectiles of up to 8 inches in diameter at speeds of up to Mach 20</td>
<td>Arnold AFB, TN</td>
</tr>
<tr>
<td>Holloman High Speed Test Track</td>
<td>59,971 ft. track; launches projectiles at speeds of up to Mach 8</td>
<td>Holloman AFB, NM</td>
</tr>
<tr>
<td>Air Force Research Laboratory (AFRL) Cells 18, 22</td>
<td>Mach 3-7</td>
<td>Wright-Patterson AFB, OH</td>
</tr>
<tr>
<td>AFRL Laser Hardened Materials Evaluation Laboratory (LHMEL)</td>
<td>High-temperature materials testing</td>
<td>Wright-Patterson AFB, OH</td>
</tr>
<tr>
<td>AFRL Mach 6 High Reynolds Number (Re) Facility</td>
<td>10-inch Mach 6</td>
<td>Wright-Patterson AFB, OH</td>
</tr>
<tr>
<td>Test Resource Management Center Hypersonic Aeropropulsion Clean Air</td>
<td>Up to Mach 8; up to 4040 °F</td>
<td>Arnold AFB, TN</td>
</tr>
<tr>
<td>Test-bed Facility</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


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132 The following information is derived from the 2014 report (U//FOUO) Paul F. Piscopo et al., *(U) Study on the Ability of the U.S. Test and Evaluation Infrastructure,* and therefore, may not be current. Permission to use this material has been granted by the Office of Science and Technology Policy.
### Table A-2. DOD Open-Air Ranges

<table>
<thead>
<tr>
<th>Range</th>
<th>Location</th>
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</thead>
<tbody>
<tr>
<td>Ronald Reagan Ballistic Missile Defense Test Site</td>
<td>Kwajalein, Republic of the Marshall Islands</td>
</tr>
<tr>
<td>Pacific Missile Range Facility (PMRF)</td>
<td>Kauai, HI</td>
</tr>
<tr>
<td>Western Range, 30th Space Wing</td>
<td>Vandenberg AFB, CA</td>
</tr>
<tr>
<td>Naval Air Warfare Center Weapons (NAWC) Division</td>
<td>Point Mugu and China Lake, CA</td>
</tr>
<tr>
<td>White Sands Missile Range (WSMR)</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Eastern Range, 45th Space Wing</td>
<td>Cape Canaveral Air Force Station/Patrick AFB/Kennedy Space Center, FL</td>
</tr>
<tr>
<td>NASA Wallops Flight Facility</td>
<td>Wallops Island, VA</td>
</tr>
<tr>
<td>Pacific Spaceport Complex (formerly Kodiak Launch Complex)</td>
<td>Kodiak Island, AK</td>
</tr>
<tr>
<td>NAWC Weapons Division R-2508 Complex</td>
<td>Edwards AFB, CA</td>
</tr>
<tr>
<td>Utah Test and Training Range</td>
<td>Utah</td>
</tr>
<tr>
<td>Nevada Test and Training Range</td>
<td>Nevada</td>
</tr>
</tbody>
</table>

**Source:** (U/FOUO) Paul F. Piscopo et al.

### Table A-3. DOD Mobile Assets

<table>
<thead>
<tr>
<th>Asset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navy Mobile Instrumentation System</td>
</tr>
<tr>
<td>PMRF Mobile At-sea Sensor System</td>
</tr>
<tr>
<td>MDA Mobile Instrumentation System Pacific Collector</td>
</tr>
<tr>
<td>MDA Mobile Instrumentation System Pacific Tracker</td>
</tr>
<tr>
<td>Kwajalein Mobile Range Safety System 2</td>
</tr>
<tr>
<td>United States Navy Ship Lorenzen missile range instrumentation ship</td>
</tr>
<tr>
<td>Sea-based X-band Radar</td>
</tr>
<tr>
<td>Aircraft Mobile Instrumentation Systems</td>
</tr>
<tr>
<td>Transportable Range Augmentation and Control System</td>
</tr>
<tr>
<td>Re-locatable MPS-36 Radar</td>
</tr>
<tr>
<td>Transportable Telemetry System</td>
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</tbody>
</table>

**Source:** (U/FOUO) Paul F. Piscopo et al.
### Table A-4. NASA Research-Related Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capability</th>
<th>Location</th>
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<tbody>
<tr>
<td>Ames Research Center (ARC) Arc Jet Complex</td>
<td>High-temperature materials testing</td>
<td>Mountain View, CA</td>
</tr>
<tr>
<td>ARC Hypervelocity Free Flight Facilities</td>
<td>Launches projectiles at speeds of up to Mach 23</td>
<td>Mountain View, CA</td>
</tr>
<tr>
<td>Langley Research Center (LaRC) Aerothermodynamics Laboratory</td>
<td>31-inch Mach 10, 20-inch Mach 6, and 15-inch Mach 6</td>
<td>Hampton, VA</td>
</tr>
<tr>
<td>LaRC 8-foot High Temperature Tunnel</td>
<td>96-inch Mach 5 and Mach 6.5</td>
<td>Hampton, VA</td>
</tr>
<tr>
<td>LaRC Scramjet Test Complex</td>
<td>Up to Mach 8 and up to 4740 °F</td>
<td>Hampton, VA</td>
</tr>
<tr>
<td>LaRC HyPulse Facility</td>
<td>Currently inactive</td>
<td>Long Island, NY</td>
</tr>
<tr>
<td>Glenn Research Center (GRC) Plumbrock Hypersonic Tunnel Facility Arc Jet Facility</td>
<td>Mach 5, 6, and 7 and up to 3830 °F</td>
<td>Sandusky, OH</td>
</tr>
<tr>
<td>GRC Propulsion Systems Laboratory 4</td>
<td>Mach 6</td>
<td>Cleveland, OH</td>
</tr>
<tr>
<td>GRC 1’ x 1’ Supersonic Wind Tunnel</td>
<td>12-inch Mach 1.3-6 (10 discrete airspeeds) and up to 640 °F</td>
<td>Cleveland, OH</td>
</tr>
</tbody>
</table>

**Source:** (U//FOUO) Paul F. Piscopo et al.

### Table A-5. Department of Energy Research-Related Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capability</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandia National Laboratories Solar Thermal Test Facility</td>
<td>High-temperature materials testing and aerodynamic heating simulation</td>
<td>Albuquerque, NM</td>
</tr>
<tr>
<td>Sandia National Laboratories Hypersonic Wind Tunnel</td>
<td>18-inch Mach 5, 8, and 14</td>
<td>Albuquerque, NM</td>
</tr>
</tbody>
</table>

**Source:** (U//FOUO) Paul F. Piscopo et al.

### Table A-6. Industry/Academic Research-Related Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capability</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUBRC Large Energy National Shock (LENS)-I/-II/-XX Tunnels</td>
<td>LENS I: Mach 6-22</td>
<td>Buffalo, NY</td>
</tr>
<tr>
<td></td>
<td>LENS II: Mach 2-12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LENS XX: Atmospheric reentry simulation</td>
<td></td>
</tr>
<tr>
<td>Boeing Polysonic Wind Tunnel</td>
<td>48-inch up to Mach 5</td>
<td>St. Louis, MO</td>
</tr>
<tr>
<td>Lockheed Martin High Speed Wind Tunnel</td>
<td>48-inch Mach 3-5</td>
<td>Dallas, TX</td>
</tr>
<tr>
<td>Boeing/Air Force Office of Scientific Research (AFOSR) Quiet Tunnel at Purdue University</td>
<td>9.5-inch Mach 6</td>
<td>West Lafayette, IN</td>
</tr>
</tbody>
</table>
AFOSR-University of Notre Dame          24-inch Mach 6          Notre Dame, IN
Quiet Tunnel                                

Stratolaunch Carrier Aircraft          Reusable Mach 6 test bed          N/A 

**Sources:** (U//FOUO) Paul F. Piscopo et al.; Oriana Pawlyk, “Air Force Expanding Hypersonic Technology Testing”; University of Arizona, “Mach 5 Quiet Ludwieg Tube”; and Ashley Tressel, “Army to open hypersonic testing facility.”

**Notes:** Hypersonic wind tunnels are under construction at the following universities: Texas A&M University (Mach 10 quiet tunnel expected to be complete in 2021), the University of Arizona (Mach 5 quiet tunnel expected to be complete in 2021), Purdue University (Mach 8 quiet tunnel expected to be complete in 2022), and the University of Notre Dame (Mach 10 quiet tunnel expected to be complete in 2023). Additional universities, such as the University of Maryland, the California Institute of Technology, the Georgia Institute of Technology, the Air Force Academy, the University of Tennessee Space Institute, and Virginia Polytechnic Institute and State University, also maintain experimental hypersonic facilities or conduct hypersonic research.

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