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Hypersonic Weapons: Background and Issues for Congress

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SUMMARY

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Hypersonic Weapons: Background and Issues for Congress

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 former 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 FY2023 budget request for hypersonic research is $4.7 billion—up from $3.8 billion in the FY2022 request. The Missile Defense Agency additionally requested $225.5 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.[1] 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."[2] 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.[3] 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.

[2] U.S. Congress, Senate Committee on Armed Services, "Testimony of Michael Griffin," Hearing on New Technologies to Meet Emerging Threats, April 18, 2018, at https://www.armed-services.senate.gov/imo/media/doc/18-40_04-18-18.pdf.

[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, at https://aviationweek.com/defense-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.[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."[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).[6] There are two primary categories of hypersonic weapons:

- **Hypersonic glide vehicles (HGV)** are launched from a rocket before gliding to a target.[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 former 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."[8] Conventional hypersonic weapons use only kinetic energy—energy derived from motion—to destroy unhardened targets or, potentially, underground facilities.[9]

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

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[4] P.L. 115-232, Section 2, Division A, Title II, §247.

[5] P.L. 115-232, Section 2, Division A, Title XVI, §1689.

[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, at https://www.rand.org/pubs/research_reports/RR2137.html; and Mike Yeo, "Japan unveils its hypersonic weapons plans," *Defense News*, March 14, 2020.

[7] When HGVs are mated with their rocket booster, the resulting weapon system is often referred to as a hypersonic boost-glide weapon.

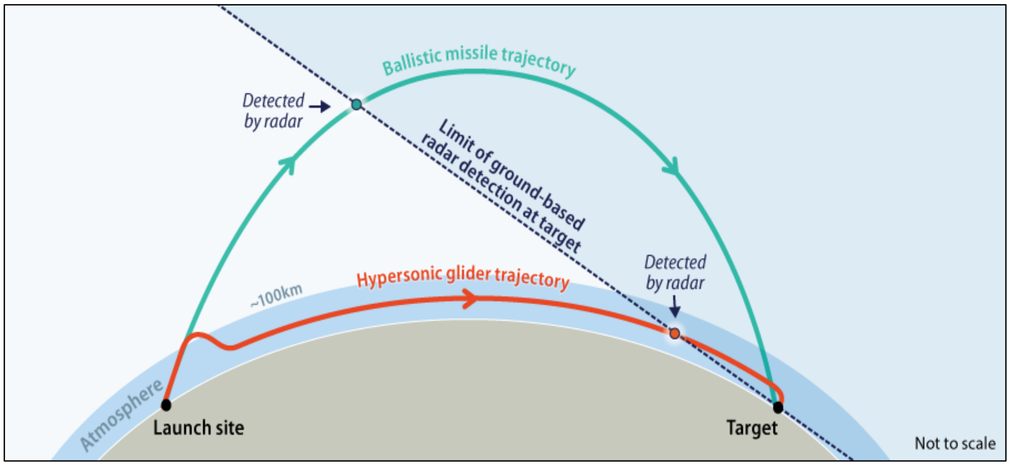
[8] U.S. Congress, Senate Committee on Armed Services, "Testimony of John E. Hyten," Hearing on United States Strategic Command and United States Northern Command, February 26, 2019, at https://www.armed-services.senate.gov/imo/media/doc/Hyten_02-26-19.pdf.

[9] Richard H. Speier et al., *Hypersonic Missile Proliferation: Hindering the Spread of a New Class of Weapons*, p. 13.

[10] See Department of Defense, *2019 Missile Defense Review*, at https://www.defense.gov/Portals/1/Interactive/2018/11-2019-Missile-Defense-Review/The%202019%20MDR_Executive%20Summary.pdf.

[11] Richard H. Speier et al., *Hypersonic Missile Proliferation: Hindering the Spread of a New Class of Weapons*.

Figure 1. Terrestrial-Based Detection of Ballistic Missiles vs. Hypersonic Glide Vehicles



Source: CRS image based on an image in "Gliding missiles that fly faster than Mach 5 are coming," *The Economist*, April 6, 2019, https://www.economist.com/science-and-technology/2019/04/06/gliding-missiles-that-fly-faster-than-mach-5-are-coming.

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.[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."[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[14]—could theoretically present viable options for defending against hypersonic weapons in the future.[15] 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."[16]

[12] Bradley Perrett et al., "U.S. Navy sees Chinese HGV as part of Wider Threat," *Aviation Week*, January 27, 2014.

[13] David Vergun, "DOD Scaling Up Effort to Develop Hypersonics," *DoD News*, December 13, 2018, at https://dod.defense.gov/News/Article/Article/1712954/dod-scaling-up-effort-to-develop-hypersonics/; see also U.S. Congress, Senate Committee on Armed Services, "Testimony of Michael Griffin," Hearing on New Technologies to Meet Emerging Threats, April 18, 2018, at https://www.armed-services.senate.gov/imo/media/doc/18-40_04-18-18.pdf, and U.S. Congress, Senate Committee on Armed Services, "Testimony of John E. Hyten," Hearing on United States Strategic Command and United States Northern Command, February 26, 2019, at https://www.armed-services.senate.gov/imo/media/doc/Hyten_02-26-19.pdf.

[14] Section 1664 of the FY2022 NDAA (P.L. 117-81) granted the "Director of the Missile Defense Agency the authority to budget for, direct, and manage directed energy programs applicable for ballistic and hypersonic missile defense missions, in coordination with other directed energy efforts of the Department of Defense."

[15] U.S. Congress, Senate Committee on Armed Services, "Testimony of Michael Griffin," Hearing on New Technologies to Meet Emerging Threats, April 18, 2018, at https://www.armed-services.senate.gov/imo/media/doc/18-40_04-18-18.pdf; and U.S. Congress, Senate Committee on Armed Services, "Testimony of John E. Hyten," Hearing on United States Strategic Command and United States Northern Command, February 26, 2019, at https://www.armed-services.senate.gov/imo/media/doc/Hyten_02-26-19.pdf.

[16] Department of Defense, *2019 Missile Defense Review*, p. XVI, at https://www.defense.gov/Portals/1/Interactive/

Other analysts have questioned the affordability, technological feasibility, and/or utility of wide-area hypersonic weapons defense.[17] 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 would need an unaffordable number of THAAD batteries."[18] 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."[19] (For additional information on hypersonic missile defense, see CRS In Focus IF11623, *Hypersonic Missile Defense: Issues for Congress*, by Kelley M. Sayler.)

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.[20] 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.[21] 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."[22] 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.[23]

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

2018/11-2019-Missile-Defense-Review/The%202019%20MDR_Executive%20Summary.pdf.

[17] See James M. Acton, "Hypersonic Weapons Explainer," Carnegie Endowment for International Peace, April 2, 2018, at https://carnegieendowment.org/2018/04/02/hypersonic-weapons-explainer-pub-75957; and Margot van Loon, "Hypersonic Weapons: A Primer."

[18] Acton, "Hypersonic Weapons Explainer."

[19] Margot van Loon, "Hypersonic Weapons: A Primer" in *Defense Technology Program Brief: Hypersonic Weapons*, American Foreign Policy Council, May 17, 2019. Some analysts have suggested that future command and control systems may require autonomous functionality to manage the speed and unpredictability of hypersonic weapons. See John L. Dolan, Richard K. Gallagher, and David L. Mann, "Hypersonic Weapons Are Literally Unstoppable (As in America Can't Stop Them)," *Real Clear Defense*, April 23, 2019, at https://www.realcleardefense.com/articles/2019/04/23/hypersonic_weapons__a_threat_to_national_security_114358.html.

[20] 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.

[21] Roger Zakheim and Tom Karako, "China's Hypersonic Missile Advances and U.S. Defense Responses," Remarks at the Hudson Institute, March 19, 2019. See also Department of Defense Fiscal Year (FY) 2020 Budget Estimates, Army Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, p. 580.

[22] Department of Defense, "Summary of the 2018 National Defense Strategy of The United States of America," p. 3, at https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf.

[23] House Armed Services Committee, *Future of Defense Task Force Report 2020*, September 2020, at https://armedservices.house.gov/_cache/files/2/6/26129500-d208-47ba-a9f7-25a8f82828b0/424EB2008281A3C79BA8C7EA71890AE9.future-of-defense-task-force-report.pdf.

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.[24]

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**):

- U.S. Navy—Conventional Prompt Strike (CPS);
- U.S. Navy—Offensive Anti-Surface Warfare Increment 2 (OASuW Inc 2), also known as Hypersonic Air-Launched OASuW (HALO);
- 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 follow-on (MoHAWC, pronounced "mohawk").

These programs are intended to produce operational prototypes, as there are currently no programs of record for hypersonic weapons.[25]

U.S. Navy

In a June 2018 memorandum, DOD announced that the Navy would lead the development of a Common Hypersonic Glide Body for use across the services.[26] The glide body is being adapted from a Mach 6 Army prototype warhead, the Alternate Re-Entry System. The Navy's Conventional Prompt Strike (CPS) is expected to pair the glide body with a booster system to create a common All Up Round (AUR) for use by both the Navy and Army. The first test of the AUR, conducted in June 2022, resulted in failure.[27]

According to the Navy's FY2023 budget documents, the Navy intends to conduct testing in support of CPS's deployment on Zumwalt-class destroyers by FY2025.[28] Although Navy officials have previously noted plans to achieve "limited operating capability" on Ohio-class submarines

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[24] James M. Acton, "China's Advanced Weapons," Testimony to the U.S. China Economic and Security Review Commission, February 23, 2017, at https://carnegieendowment.org/2017/02/23/china-s-advanced-weapons-pub-68095.

[25] Steve Trimble, "New Long-Term Pentagon Plan Boosts Hypersonics, But Only Prototypes," *Aviation Week*, March 15, 2019, at https://aviationweek.com/defense/new-long-term-pentagon-plan-boosts-hypersonics-only-prototypes.

[26] The services coordinate efforts on a Common Hypersonic Glide Body Board of Directors with rotating chairmanship. Sydney J. Freedberg Jr., "Army Ramps up Funding for Laser Shield, Hypersonic Sword," *Breaking Defense*, February 28, 2020, at https://breakingdefense.com/2020/02/army-ramps-up-funding-for-laser-shield-hypersonic-sword/.

[27] Jon Herskovitz and Anthony Capaccio, "US Hypersonic Missile Fails in Test in Fresh Setback for Program," *Bloomberg*, June 29, 2022, at https://www.bloomberg.com/news/articles/2022-06-30/us-hypersonic-missile-fails-in-test-in-fresh-setback-for-program.

[28] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Navy Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, p. 1458, at https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/RDTEN_BA4_Book.pdf.

as early as 2025[29] and on Virginia-class submarines by FY2028, as well as to eventually field hypersonic weapons on Burke-class destroyers, such plans are not reflected in FY2023 budget documents.[30] The Navy is requesting $1.2 billion for CPS RDT&E in FY2023—a decrease of $169 million from the FY2022 request and $120 million from the FY2022 appropriation.[31]

The Navy is also developing the Offensive Anti-Surface Warfare Increment 2 (OASuW Inc 2), also known as Hypersonic Air-Launched OASuW (HALO)—a new start in FY2023.[32] Although few details about the program have been released publicly, HALO is likely to be compatible with the Navy's F/A-18 fighter jet.[33] The Navy is requesting $92 million for HALO RDT&E in FY2023.[34]

U.S. Army

The Army's Long-Range Hypersonic Weapon (LRHW) 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."[35] The Army is requesting $806 million in RDT&E for the program in FY2023—$394 million over the FY2022 request and $380 million over the FY2022 appropriation.[36] It plans to field an experimental prototype in FY2023 and transition to a program

[29] See Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Navy Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, p. 1466, at https://www.secnav.navy.mil/fmc/fmb/Documents/22pres/RDTEN_BA4_Book.pdf; Department of the Navy, "Highlights of the Department of the Navy FY 2021 Budget," February 10, 2020, at https://www.secnav.navy.mil/fmc/fmb/Documents/21pres/Highlights_book.pdf; and Megan Eckstein, "Navy Says Hypersonic Weapons Coming to Subs in 5 Years," *USNI News*, November 17, 2020, at https://news.usni.org/2020/11/17/navy-says-hypersonic-weapons-coming-to-subs-in-5-years.

[30] David B. Larter, "All US Navy destroyers will get hypersonic missiles, says Trump's national security adviser," *Defense News*, October 21, 2020, at https://www.defensenews.com/naval/2020/10/21/all-us-navy-destroyers-will-get-hypersonic-missiles-trumps-national-security-advisor-says/.

[31] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Navy Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, p. 1458, at https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/RDTEN_BA4_Book.pdf.

[32] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Navy Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, p. 1373, at https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/RDTEN_BA4_Book.pdf.

[33] Joesph Trevithick, "Hypersonic Anti-Ship Cruise Missile Has To Be Ready By 2028 Navy Says," *The Drive*, April 23, 2022, at https://www.thedrive.com/the-war-zone/hypersonic-anti-ship-cruise-missile-has-to-be-ready-by-2028-navy-says.

[34] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Navy Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, p. 1373, at https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/RDTEN_BA4_Book.pdf.

[35] Sydney J. Freedberg Jr., "Army Discloses Hypersonic LRHW Range Of 1,725 Miles; Watch Out China," *Breaking Defense*, May 12, 2021, at https://breakingdefense.com/2021/05/army-discloses-hypersonic-lrhw-range-of-1725-miles-watch-out-china/; https://breakingdefense.com/2019/03/army-sets-2023-hypersonic-flight-test-strategic-cannon-advances/; and Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Army Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, p. 639, at https://www.asafm.army.mil/Portals/72/Documents/BudgetMaterial/2022/Base%20Budget/rdte/RDTE_BA_4_FY_2022_PB.pdf.

[36] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Army Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, pp. 711-726, at https://www.asafm.army.mil/Portals/72/Documents/BudgetMaterial/2023/Base%20Budget/rdte/vol_2-Budget_Activity_4.pdf; and Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Army Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 5D, p. 185, at https://www.asafm.army.mil/Portals/72/Documents/BudgetMaterial/2023/Base%20Budget/rdte/vol_2-Budget_Activity_5D.pdf.

of record in the fourth quarter of FY2024—a timeline that Army officials have termed "very, very aggressive" and that will require the program to take on "a lot of risk."[37] The Army additionally requested $249 million for the procurement of LRHW ground support equipment in FY2023.[38]

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.[39] ARRW successfully completed a "captive carry" test flight in June 2019. It then experienced three successive failures before completing three successful flight tests in 2022.[40] The most recent flight test, conducted in December 2022, was the first test of the full prototype operational ARRW.[41] The Air Force has repeatedly pushed the timeline for ARRW and now states that ARRW could be operational "as early as fall 2023."[42] The Air Force requested $115 million for ARRW RDT&E in FY2023—$123 million under the FY2022 request and $204 million under the FY2022 appropriation.[43] In addition, the Air Force requested $47 million for ARRW

[37] Jon Harper, *DefenseScoop*, October 10, 2022, at https://defensescoop.com/2022/10/10/army-assuming-a-lot-of-risk-as-it-moves-to-field-hypersonic-weapons-by-end-of-fiscal-year/. See also Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Army Justification Book of Research, Development, Test and Evaluation, Volume II, Budget Activity 4, pp. 705-709, at https://www.asafm.army.mil/Portals/72/Documents/BudgetMaterial/2023/Base%20Budget/rdte/vol_2-Budget_Activity_4.pdf.

[38] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Army Justification Book of Missile Procurement, p. 66, at https://www.asafm.army.mil/Portals/72/Documents/BudgetMaterial/2023/Base%20Budget/Procurement/MSLS_ARMY.pdf.

[39] ARRW is expected to be launched initially from the B-52H strategic bomber. Thomas Newdick, "Air Force Says New Hypersonic Missile Will Hit Targets 1,000 Miles Away In Under 12 Minutes," *The Drive*, October 13, 2020, at https://www.thedrive.com/the-war-zone/37045/air-force-says-new-hypersonic-missile-will-hit-targets-1000-miles-away-in-under-12-minutes.

[40] Oriana Pawlyk, "Air Force's Hypersonic ARRW Missile Fails First Flight Test," *Military.com*, April 6, 2021, at https://www.military.com/daily-news/2021/04/06/air-forces-hypersonic-arrw-missile-fails-first-flight-test.html#:~:text=In%20June%202019%2C%20the%20service,early%202020s%2C%20the%20release%20states; John A. Tirpak, "Hypersonic ARRW Flies Successfully for Second Time, Completing Booster Tests," *Air Force Magazine*, July 13, 2022, at https://www.airforcemag.com/hypersonic-arrw-flies-successfully-for-second-time-completing-booster-tests/.

[41] Ilka Cole, "Air Force conducts first ARRW operational prototype missile test," U.S. Air Force, December 12, 2022, at https://www.af.mil/News/Article-Display/Article/3243194/air-force-conducts-first-arrw-operational-prototype-missile-test/.

[42] Nicole Ledbetter, "AFGSC takes next steps in making Air Force's first hypersonic weapon," U.S. Air Force 2nd Bomb Wing Public Affairs, December 4, 2022, at https://www.af.mil/News/Article-Display/Article/3234145/afgsc-takes-next-steps-in-making-air-forces-first-hypersonic-weapon/. As recently as March 2022, the Air Force asserted that ARRW could reach early operational capability in late 2022. See Anthony Capaccio, "Hypersonic-Missile Failures Risk U.S. Chase of China, Russia," *Bloomberg*, March 7, 2022, at https://www.bloomberg.com/news/articles/2022-03-07/hypersonic-missile-failures-imperil-u-s-chase-of-china-russia.

[43] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Air Force Justification Book of Research, Development, Test and Evaluation, Volume II, p. 145, at https://www.saffm.hq.af.mil/Portals/84/documents/FY23/RDTE_/FY23%20Air%20Force%20Research%20Development%20Test%20and%20Evaluation%20Vol%20II.pdf?ver=LK67U_ThMsX7AwahfurKGw%3d%3d.

procurement in FY2023;[44] however, Air Force officials have stated that they will submit a reprogramming request to shift these funds to ARRW RDT&E.[45]

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.[46] 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.[47] A senior Air Force official has since noted that a B-52 could potentially carry four ARRWs.[48]

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,[49] with a senior Air Force official noting that a B-52 could potentially carry 20 HACMs or more.[50] According to the Air Force, "the ability to execute HACM development is contingent upon fully funded and successful predecessor capability development efforts."[51] The Air Force requested $317 million for HACM in FY2023, up from $200 million in the FY2022 request and $190 million in the FY2022 appropriation.[52]

44 Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Air Force Justification Book of Missile Procurement, Volume I, p. 23, at https://www.saffm.hq.af.mil/Portals/84/documents/FY23/PROCUREMENT_/FY23%20Air%20Force%20Missile%20Procurement.pdf?ver=QeRLpOSY7vcLmsKbr3C-Qw%3d%3d. The Air Force requested $161 million in FY2022 for the procurement of an estimated 12 ARRW missiles. Congress authorized $116 million for ARRW procurement in the FY2022 NDAA (P.L. 117-81), noting that additional funds were "early to need." Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Air Force Justification Book of Missile Procurement, Volume I, p. 19, at https://www.saffm.hq.af.mil/Portals/84/documents/FY22/PROCUREMENT_/FY22%20DAF%20J-Book%20-%203020%20-%20Missile%20Proc.pdf?ver=GIEj1YH2GS-elMys1wLm1A%3d%3d. https://www.saffm.hq.af.mil/Portals/84/documents/FY22/PROCUREMENT_/FY22 DAF J-Book - 3020 - Missile Proc.pdf?ver=GIEj1YH2GS-elMys1wLm1A%3d%3d.

45 Valerie Insinna, "Air Force ditches plans to buy first hypersonic ARRW missile in FY23," *Breaking Defense*, March 29, 2022, at https://breakingdefense.com/2022/03/air-force-ditches-plans-to-buy-first-hypersonic-arrw-missile-in-fy23/.

46 Valerie Insinna, "US Air Force kills one of its hypersonic weapons programs," *Defense News*, February 10, 2020, at https://www.defensenews.com/smr/federal-budget/2020/02/10/the-air-force-just-canceled-one-of-its-hypersonic-weapons-programs/.

47 John A. Tirpak, "Roper: The ARRW Hypersonic Missile Better Option for USAF," *Air Force Magazine*, March 2, 2020, at https://www.airforcemag.com/arrw-beat-hcsw-because-its-smaller-better-for-usaf/. Tirpak additionally notes that "the F-15 could accelerate the ARRW to Mach 3 before launch, potentially reducing the size of the booster needed to get the weapon to hypersonic speed."

48 John A. Tirpak, "Air Force Will Try Again to Launch ARRW Hypersonic Missile in July," *Air Force Magazine*, June 3, 2021, at https://www.airforcemag.com/air-force-july-launch-arrw-hypersonic-missile/.

49 FY2023 Air Force budget documents note that "the HACM program will prioritize integration on the F-15E platform to enable quick entry into flight test."

50 John A. Tirpak, "Air Force Will Try Again to Launch ARRW Hypersonic Missile in July," *Air Force Magazine*, June 3, 2021, at https://www.airforcemag.com/air-force-july-launch-arrw-hypersonic-missile/.

51 Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Air Force Justification Book of Research, Development, Test and Evaluation, Volume II, p. 148, at https://www.saffm.hq.af.mil/Portals/84/documents/FY22/RDTE_/FY22%20DAF%20J-Book%20-%203600%20-%20AF%20RDT%20and%20E%20Vol%20II.pdf?ver=KpJJbVq68o32dSvkjuv_Iw%3d%3d.

52 Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Air Force Justification Book of Research, Development, Test and Evaluation, Volume II, p. 145 and 161, at https://www.saffm.hq.af.mil/Portals/84/documents/FY23/RDTE_/FY23%20Air%20Force%20Research%20Development%20Test%20and%20Evaluation%20Vol%20II.pdf?ver=

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."[53] Mayhem is reported to be larger than ARRW and capable of carrying multiple payloads for different mission sets.[54]

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."[55] 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 $30 million for TBG in FY2023—$20 million under the FY2022 request and appropriation.[56]

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." OpFires completed its first flight test in July 2022.[57] DARPA requested and received $45 million for OpFires in FY2022, but did not request funds in FY2023, following the program's completion.[58]

DARPA has similarly concluded work on the Hypersonic Air-breathing Weapon Concept (HAWC), which, with Air Force support, sought "to develop and demonstrate critical

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LK67U_ThMsX7AwahfurKGw%3d%3d; and Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Air Force Justification Book of Research, Development, Test and Evaluation, Volume II, p. 139, at https://www.saffm.hq.af.mil/Portals/84/documents/FY22/RDTE_/FY22%20DAF%20J-Book%20-%203600%20-%20AF%20RDT%20and%20E%20Vol%20II.pdf?ver=KpJJbVq68o32dSvkjuv_Iw%3d%3d.

[53] Mike White, Remarks at the Center for Strategic and International Studies, "Hypersonic Strike and Defense: A Conversation with Mike White," June 10, 2021, at https://www.csis.org/analysis/hypersonic-strike-and-defense-conversation-mike-white.

[54] See, for example, Rachel S. Cohen, "Hypersonic Attack Cruise Missile Becomes High-Priority USAF Project," Air Force Magazine, October 13, 2020, at https://www.airforcemag.com/hypersonic-attack-cruise-missile-becomes-highpriority-usaf-project/.

[55] "Tactical Boost Glide (TBG) Program Information," DARPA, https://www.darpa.mil/program/tactical-boost-glide; and Guy Norris, "U.S. Air Force Plans Road Map to Operational Hypersonics," *Aviation Week*, July 27, 2017, at https://aviationweek.com/defense/us-air-force-plans-road-map-operational-hypersonics.

[56] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 171, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2023.pdf; and Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 158, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2022/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2022.pdf.

[57] DARPA, "Operational Fires Program Successfully Completes First Flight Test," July 13, 2022, at https://www.darpa.mil/news-events/2022-07-13a.

[58] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 172, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2023.pdf; and Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 159, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2022/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2022.pdf.

technologies to enable an effective and affordable air-launched hypersonic cruise missile."[59] DARPA successfully tested HAWC in March and July 2022, launching the missile from a B-52 bomber.[60] Principal Director for Hypersonics Mike White has stated that hypersonic cruise missiles like HAWC would be smaller than 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.[61] DARPA requested and received $10 million to develop HAWC in FY2022.[62] DARPA requested $60 million for MoHAWC, the successor program to HAWC, in FY2023.[63] Like HAWC, MoHAWC seeks to develop technologies for use in future air-launched hypersonic cruise missiles.[64]

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

Title	FY2022 Request ($ in millions)	FY2022 Enacted ($ in millions)	PB2023 ($ in millions)	Schedule
Conventional Prompt Strike (CPS)	1,374	1,325	1,205	Platform deployment in FY2025 and FY2028
Hypersonic Air-Launched OASuW (HALO)	0	0	92	Field in FY2028
Long-Range Hypersonic Weapon (LRHW)	412	426	806	Prototype deployment in FY2023
AGM-183 Air-Launched Rapid Response Weapon (ARRW)	238	319	115	Flight tests through FY2023
Hypersonic Attack Cruise Missile (HACM)	200	190	462	Complete test and development in FY2027
Tactical Boost Glide (TBG)	50	50	30	Complete third test flight in FY2023

[59] "Hypersonic Air-breathing Weapon Concept (HAWC) Program Information," DARPA, at https://www.darpa.mil/program/hypersonic-air-breathing-weapon-concept.

[60] Oren Liebermann, "US tested hypersonic missile in mid-March but kept it quiet to avoid escalating tensions with Russia," *CNN*, April 5, 2022, at https://us.cnn.com/2022/04/04/politics/us-hypersonic-missile-test/index.html; and Courtney Albon, "Raytheon hypersonic scramjet missile has another successful flight test," *Defense News*, July 19, 2022, at https://www.defensenews.com/battlefield-tech/2022/07/19/darpas-hypersonic-scramjet-missile-logs-another-flight-test-success/?utm_source=sailthru&utm_medium=email&utm_campaign=dfn-ebb&SToverlay=2002c2d9-c344-4bbb-8610-e5794efcfa7d.

[61] "Department of Defense Press Briefing on Hypersonics," March 2, 2020, at https://www.defense.gov/Newsroom/Transcripts/Transcript/Article/2101062/department-of-defense-press-briefing-on-hypersonics/.

[62] Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 161, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2022/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2022.pdf.

[63] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 173, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2023.pdf.

[64] Ibid.

Title	FY2022 Request ($ in millions)	FY2022 Enacted ($ in millions)	PB2023 ($ in millions)	Schedule
Hypersonic Air-breathing Weapon Concept (HAWC)/ MoHAWC	10	10	60	Begin integration and ground testing in FY2023

Source: Program information taken from U.S. Navy, Army, Air Force, and DARPA FY2022 and FY2023 Justification Books, available at https://comptroller.defense.gov/Budget-Materials/.

Note: MoHAWC, a new start in FY2023, is the successor program to HAWC, which concluded in FY2022.

Hypersonic Missile Defenses[65]

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.[66] In September 2018, the Missile Defense Agency (MDA)—which in 2017 established a Hypersonic Defense Program pursuant to Section 1687 of the FY2017 NDAA (H.Rept. 114-840)—commissioned 21 white papers to explore hypersonic missile defense options, including interceptor missiles, hypervelocity projectiles, laser guns, and electronic attack systems.[67] In January 2020, MDA issued a draft request for prototype proposals for a Hypersonic Defense Regional Glide Phase Weapons System interceptor intended to be fielded in the mid-2030s; however, the program was later cancelled in favor of a nearer-term solution, the Glide Phase Intercept (GPI).[68] MDA seeks to field a regional, sea-based GPI capability in the mid- to late 2020s.[69] In addition, MDA is developing the Hypersonic and Ballistic Tracking Space Sensor (HBTSS)—which it hopes to launch in March 2023—in an effort to improve the agency's ability to detect and track incoming missiles.[70] MDA requested $89.2 million for HBTSS in FY2023; the agency requested $225.5 million for hypersonic defense in FY2023—down from its $247.9 million FY2022 request and $287.8 million FY2022 appropriation.[71] Finally, DARPA is working on a program called Glide Breaker, which "will

[65] For additional information about hypersonic missile defense, see CRS In Focus IF11623, *Hypersonic Missile Defense: Issues for Congress*, by Kelley M. Sayler.

[66] "Media Availability With Deputy Secretary Shanahan and Under Secretary of Defense Griffin at NDIA Hypersonics Senior Executive Series," U.S. Department of Defense, December 13, 2018, at https://dod.defense.gov/News/Transcripts/Transcript-View/Article/1713396/media-availability-with-deputy-secretary-shanahan-and-under-secretary-of-defens/.

[67] H.Rept. 114-840, Section 2, Division A, Title XVI, §1687; Hudson and Trimble, "Top U.S. Hypersonic Weapon Program"; and Steve Trimble, "A Hypersonic Sputnik?," p. 21.

[68] Missile Defense Agency, "Draft Request for Prototype Proposal: Hypersonic Defense Regional Glide Phase Weapon System," January 30, 2020, p. 8; and Steve Trimble, "MDA Unveils GPI In Retooled Counter-Hypersonic Plan," *Aviation Week*, February 4, 2021, at https://aviationweek.com/defense-space/missile-defense-weapons/mda-unveils-gpi-retooled-counter-hypersonic-plan.

[69] Steve Trimble, "MDA Unveils GPI In Retooled Counter-Hypersonic Plan," *Aviation Week*, February 4, 2021, at https://aviationweek.com/defense-space/missile-defense-weapons/mda-unveils-gpi-retooled-counter-hypersonic-plan.

[70] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Missile Defense Agency, Defense-Wide Justification Book 2a of 5, p. 841, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol2_MDA_RDTE_PB23_Justification_Book.pdf; and *Defense Budget Overview: United States Department of Defense Fiscal Year 2023 Budget Request*, Office of the Under Secretary of Defense (Comptroller)/Chief Financial Officer, April 2022, p. 2-15, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/FY2023/FY2023_Budget_Request_Overview_Book.pdf.

[71] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Missile Defense Agency, Defense-Wide Justification Book 2a of 5, p. 631 and 853, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/

develop critical component technology to support a lightweight vehicle designed for precise engagement of hypersonic threats at very long range."[72] DARPA requested $18 million for Glide Breaker in FY2023, up from its $7 million request and appropriation in FY2022.[73]

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),[74] 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.[75] These specialized facilities, which simulate the unique conditions experienced in hypersonic flight (e.g., speed, pressure, heating),[76] 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.[77] 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.[78] 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.[79] The United States

budget_justification/pdfs/03_RDT_and_E/RDTE_Vol2_MDA_RDTE_PB23_Justification_Book.pdf; and Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Missile Defense Agency, Defense-Wide Justification Book 2a of 5, p. 569, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2022/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol2_MDA_RDTE_PB22_Justification_Book.pdf.

[72] Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 164.

[73] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 169, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2023.pdf; and Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Defense Advanced Research Projects Agency, Defense-Wide Justification Book 1 of 5, p. 160, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2022/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2022.pdf.

[74] P.L. 112-239, Section 2, Division A, Title X, §1071.

[75] 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, at https://www.gao.gov/products/gao-21-378.

[76] These conditions additionally require the development of specialized materials such as metals and ceramics.

[77] 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.

[78] Oriana Pawlyk, "Air Force Expanding Hypersonic Technology Testing at Two Indiana Universities," Military.com, April 23, 2019, at https://www.military.com/daily-news/2019/04/23/air-force-expanding-hypersonic-technology-testing-two-indiana-universities.html.

[79] University of Arizona, "Mach 5 Quiet Ludwieg Tube," at https://transition.arizona.edu/facilities/qlt5?_ga=

also uses the Royal Australian Air Force Woomera Test Range in Australia and the Andøya Rocket Range in Norway for flight testing.[80] (For a partial list of U.S. hypersonic test assets and their capabilities, see the **Appendix**.)

In February 2022, DOD's Office of Inspector General announced that it had concluded its two-year-long evaluation of current ground test and evaluation facilities to determine if the capability and capacity would be sufficient to execute DOD's planned test schedule; however, DOD did not release the evaluation to the public.[81] Similarly, an annual report by DOD's Director of Test and Evaluation evaluated the sufficiency of U.S. hypersonic weapons test infrastructure; this report was not released publicly.[82]

DOD reportedly plans to expand hypersonic test infrastructure in the coming years. 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.[83] DOD has also announced the planned construction of the Multi-Service Advanced Capability Hypersonics Test Bed (MACH-TB), which is to "increase domestic capacity for hypersonic flight testing and leverage multiple commercially-available launch vehicles for ride-along hypersonic payloads."[84]According to an assessment conducted by the Government Accountability Office, DOD has dedicated approximately $1 billion to hypersonic facility modernization from FY2015 to FY2024.[85]

Congress has also continued to express interest in hypersonic weapons infrastructure. 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

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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.

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

[81] See Department of Defense Office of Inspector General, "Memorandum for Distribution: Evaluation of the Ground Test and Evaluation Infrastructure Supporting Hypersonic Capabilities (Project No. D2020-DEV0SN-0106.000)," April 13, 2020, at https://media.defense.gov/2020/Apr/14/2002280826/-1/-1/1/D2020-DEV0SN-0106.000.PDF; and Department of Defense Office of Inspector General," Evaluation of the Ground Test and Evaluation Infrastructure Supporting Hypersonic Capabilities (DODIG-2022-056)," February 3, 2022, at https://www.dodig.mil/reports.html/Article/2921419/evaluation-of-the-ground-test-and-evaluation-infrastructure-supporting-hyperson/.

[82] Anthony Capaccio, "Pentagon Hypersonic Weapons Tests Need More Wide-Open Spaces," *Bloomberg*, February 3, 2020.

[83] "Update: US Navy to develop China Lake to support CPS weapon testing," *Jane's* (subscription required), February 12, 2019, at https://janes.ihs.com/Janes/Display/FG_1644858-JMR.

[84] U.S. Department of Defense, "DoD Announces New Contract to Increase Hypersonic Flight Testing Tempo," October 6, 2022, at https://www.defense.gov/News/Releases/Release/Article/3182305/dod-announces-new-contract-to-increase-hypersonic-flight-testing-tempo/. According to a Dynetics press release, Dynetics is to lead a MACH-TB team composed of over 20 partners, including Peraton, Kratos Defense & Security Solutions, Stratolaunch, JRC Integrated Systems, NineTwelve Institute, Corvid, SpinLaunch, Varda, Kitty Hawk Technologies, Systima Division of Karman Space and Defense, Sandia National Laboratories, Oak Ridge National Laboratory, X-Bow Systems, RLNS and other hypersonic experts. See PRNewswire, "Dynetics Awarded New Contract to Increase Hypersonic Flight Testing Tempo," October 20, 2022, at https://www.prnewswire.com/news-releases/dynetics-awarded-new-contract-to-increase-hypersonic-flight-testing-tempo-301654753.html.

[85] Government Accountability Office, *Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts*, GAO-21-378, March 22, 2021, p. 27, at https://www.gao.gov/products/gao-21-378.

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." Section 225 of the FY2022 NDAA (P.L. 117-81) requires the Secretary of Defense to identify the hypersonic facilities and capabilities of the Major Range and Test Facility Base and brief the congressional defense committees on a plan for improvement.

Finally, 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 chain.[86] DOD has also amended its "5000 series" acquisition policy in order to enhance supply chain resiliency and reduce sustainment costs.[87]

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.[88] 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."[89] 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.[90]

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.[91]

[86] Aaron Mehta, "Pentagon launches hypersonic industrial base study," *Defense News*, March 3, 2020, at https://www.defensenews.com/pentagon/2020/03/02/pentagon-launches-hypersonic-industrial-base-study/.

[87] C. Todd Lopez, "Rewrite of Acquisition Regulation Helps U.S. Build Hypersonic Arsenal More Quickly," *DOD News*, October 30, 2020, at https://www.defense.gov/Explore/News/Article/Article/2400205/rewrite-of-acquisition-regulation-helps-us-build-hypersonic-arsenal-more-quickly/.

[88] United Nations Office of Disarmament Affairs, *Hypersonic Weapons: A Challenge and Opportunity for Strategic Arms Control*, February 2019, at https://www.un.org/disarmament/publications/more/hypersonic-weapons-a-challenge-and-opportunity-for-strategic-arms-control/.

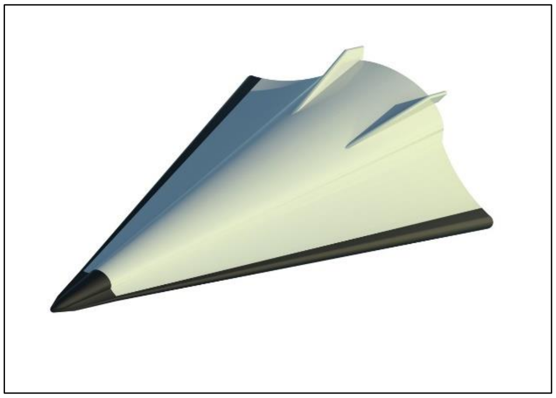
[89] Vladimir Putin, "Presidential Address to the Federal Assembly," March 1, 2018, at http://en.kremlin.ru/events/president/news/56957.

[90] In this instance, "strategic stability" refers to a "bilateral nuclear relationship of mutual vulnerability." See Tong Zhao, "Conventional Challenges to Strategic Stability: Chinese Perceptions of Hypersonic Technology and the Security Dilemma," Carnegie-Tsinghua Center for Global Policy, July 23, 2018, at https://carnegietsinghua.org/2018/07/23/conventional-challenges-to-strategic-stability-chinese-perceptions-of-hypersonic-technology-and-security-dilemma-pub-76894.

[91] 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.

Avangard (**Figure 2**) is a hypersonic glide vehicle launched from an intercontinental ballistic missile (ICBM), giving it "effectively 'unlimited' range."[92] 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 was successfully tested in April 2022 and is scheduled to be deployed by the end of 2022.[93] Avangard features onboard countermeasures and will reportedly 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.[94]

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 maximum range of approximately 625 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.[95] These sources assert that Tsirkon was successfully launched from a Project 22350 frigate in January, October, and December 2020 and from a Project 885 Yasen-class submarine in October 2021.[96] Russian news

[92] Steve Trimble, "A Hypersonic Sputnik?," *Aviation Week*, January 14-27, 2019, p. 20.

[93] Lateshia Beachum, Mary Ilyushina and Karoun Demirjian, "Russia's 'Satan 2' missile changes little for U.S., scholars say," *Washington Post*, April 20, 2022, at https://www.washingtonpost.com/world/2022/04/20/satan-2-icbm/; and Nicholas Fiorenza, "Putin outlines development of Russia's nuclear triad," *Jane's Defence Weekly* (subscription required), April 22, 2021, at https://customer.janes.com/DefenceWeekly/Display/FG_3953700-JDW. Sarmat could reportedly accommodate at least three Avangard vehicles. See Malcolm Claus, "Russia unveils new strategic delivery systems," *Jane's* (subscription required), at https://janes.ihs.com/Janes/Display/FG_899127-JIR.

[94] "First regiment of Avangard hypersonic missile systems goes on combat duty in Russia," *TASS*, December 27, 2019, at https://tass.com/defense/1104297.

[95] "Russia makes over 10 test launches of Tsirkon seaborne hypersonic missile," *TASS*, December 21, 2018, at http://tass.com/defense/1037426. See also *Russia Military Power: Building a Military to Support Great Power Aspirations*, Defense Intelligence Agency, 2017, p. 79, at https://www.dia.mil/portals/27/documents/news/military%20power%20publications/russia%20military%20power%20report%202017.pdf.

[96] "TASS: Russia Conducts First Ship-Based Hypersonic Missile Test," *Reuters*, February 27, 2020, at https://www.voanews.com/europe/tass-russia-conducts-first-ship-based-hypersonic-missile-test; and Samuel Cranny-Evans, "Russia conducts first submarine test launches of Tsirkon hypersonic missile," *Jane's* (subscription required), October 4, 2021.

sources additionally indicate that, following a successful May 2022 test, the missile will become operational by the end of 2022 and is likely to be fielded on Project 22350 frigates.[97]

In addition, Russia has fielded Kinzhal, a maneuvering air-launched ballistic missile modified from the Iskander missile. Russia reportedly fired Kinzhal from a MiG-31 interceptor aircraft in Ukraine[98] and additionally plans to deploy the missile on the Su-34 long-range strike fighter[99] and the Tu-22M3 strategic bomber, although the slower-moving bomber may face challenges in "accelerating the weapon into the correct launch parameters."[100] 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.[101]

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.[102]

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. missile defenses.[103] 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

[97] Isabel van Brugen, "Putin to Give Navy Hypersonic Missiles as Russia Beats U.S. in Arms Race," *Newsweek*, July 18, 2022, at https://www.newsweek.com/putin-russian-navy-hypersonic-missiles-zircon-1725426.

[98] Roxana Tiron, "Hypersonic Weapons: Who Has Them and Why It Matters," *Washington Post*, April 6, 2022, at https://www.washingtonpost.com/business/hypersonic-weapons-who-has-them-and-why-it-matters/2022/04/05/1f6d0280-b557-11ec-8358-20aa16355fb4_story.html.

[99] Mark B. Schneider, "Moscow's Development of Hypersonic Missiles … and What It Means" in *Defense Technology Program Brief: Hypersonic Weapons*, American Foreign Policy Council, May 17, 2019.

[100] Dave Majumdar, "Russia: New Kinzhal Aero-Ballistic Missile Has 3,000 km Range if Fired from Supersonic Bomber," *The National Interest*, July 18, 2018, at https://nationalinterest.org/blog/buzz/russia-new-kinzhal-aero-ballistic-missile-has-3000-km-range-if-fired-supersonic-bomber.

[101] David Axe, "Is Kinzhal, Russia's New Hypersonic Missile, a Game Changer?," *The Daily Beast*, March 15, 2018, at https://www.thedailybeast.com/is-kinzhal-russias-new-hypersonic-missile-a-game-changer.

[102] "Aerodynamics," Central Aerohydrodynamic Institute, http://tsagi.com/research/aerodynamics/; "Russia announces successful flight test of Avangard hypersonic glide vehicle," *Jane's* (subscription required), January 3, 2019, at https://janes.ihs.com/Janes/Display/FG_1451630-JMR; and "Avangard system is tested, said to be fully ready for deployment," Russian Strategic Nuclear Forces, December 26, 2018, at http://russianforces.org/blog/2018/12/avangard_system_is_tested_said.shtml.

[103] Tong Zhao, "Conventional Challenges to Strategic Stability: Chinese Perceptions of Hypersonic Technology and the Security Dilemma."

infrastructure. U.S. missile defense deployments could then limit China's ability to conduct a retaliatory strike against the United States.[104]

As General Terrence O'Shaughnessy, then-commander of United States Northern Command (USNORTHCOM) and North American Aerospace Defense Command (NORAD), testified in a February 2020 hearing before the Senate Armed Services Committee, China is "testing a [nuclear-capable] intercontinental-range hypersonic glide vehicle" that could evade U.S. missile defense and warning systems.[105] Reports additionally indicate that China may have tested a nuclear-capable HGV[106]—launched by a Long March rocket—in August 2021.[107] In contrast to the ballistic missiles that China has previously used to launch HGVs, the Long March, a fractional orbital bombardment system (FOBS), launches the HGV into orbit before the HGV de-orbits to its target. This could provide China with a space-based global strike capability and further reduce the amount of target warning time prior to a strike.[108]

China has also 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.[109] Furthermore, a January 2017 report found that over half of open-source Chinese papers on hypersonic weapons include references to Russian weapons programs.[110] 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.[111]

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.[112] China has also tested

[104] Tong Zhao, "Conventional Challenges to Strategic Stability"; and Lora Saalman, "China's Calculus on Hypersonic Glide," August 15, 2017, Stockholm International Peace Research Institute, at https://www.sipri.org/commentary/topical-backgrounder/2017/chinas-calculus-hypersonic-glide.

[105] General Terrence J. O'Shaughnessy, "Statement before the Senate Armed Services Committee," February 13, 2020, at https://www.armed-services.senate.gov/hearings/20-02-13-united-states-northern-command-and-united-states-strategic-command.

[106] It is not clear if this nuclear-capable HGV is the same model as that referenced by General O'Shaughnessy.

[107] Demetri Sevastopulo and Kathrin Hille, "China tests new space capability with hypersonic missile," October 16, 2021, at https://www.ft.com/content/ba0a3cde-719b-4040-93cb-a486e1f843fb. China's Foreign Ministry Spokesperson Zhao Lijian has stated that "this was a routine test of [a] space vehicle," rather than a test of a nuclear-capable HGV. Zhao Lijian, "Remarks at Regular Press Conference," Ministry of Foreign Affairs of the People's Republic of China, October 18, 2021, at https://www.fmprc.gov.cn/mfa_eng/xwfw_665399/s2510_665401/t1915130.shtml.

[108] Greg Hadley, "Kendall: China Has Potential to Strike Earth from Space," *Air Force Magazine*, September 20, 2021, at https://www.airforcemag.com/global-strikes-space-china-frank-kendall/.

[109] Lora Saalman, "China's Calculus on Hypersonic Glide."

[110] Lora Saalman, "Factoring Russia into the US-China Equation on Hypersonic Glide Vehicles," SIPRI, January 2017, at https://www.sipri.org/sites/default/files/Factoring-Russia-into-US-Chinese-equation-hypersonic-glide-vehicles.pdf.

[111] Lora Saalman, "China's Calculus on Hypersonic Glide"; and Malcolm Claus and Andrew Tate, "Chinese hypersonic programme reflects regional priorities," *Jane's* (subscription required), March 12, 2019, at https://janes.ihs.com/Janes/Display/FG_1731069-JIR.

[112] Ankit Panda, "Introducing the DF-17: China's Newly Tested Ballistic Missile Armed with a Hypersonic Glide Vehicle," *The National Interest*, December 28, 2017, at https://thediplomat.com/2017/12/introducing-the-df-17-chinas-newly-tested-ballistic-missile-armed-with-a-hypersonic-glide-vehicle/; and Bill Gertz, "China's new hypersonic missile," *Washington Times*, October 2, 2019, at https://www.washingtontimes.com/news/2019/oct/2/china-shows-df-

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.[113]

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.[114] China reportedly fielded the DF-ZF in 2020.[115]

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.[116] China claims the vehicle reached top speeds of Mach 6 and executed a series of in-flight maneuvers before landing.[117] Unlike the DF-ZF, Starry Sky-2 is a "waverider" that uses powered flight after launch and derives lift from its own shockwaves. Some reports indicate that the Starry Sky-2 could be operational by 2025.[118] U.S. officials have declined to comment on the program.[119]

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.[120] China tested three hypersonic vehicle models (D18-1S, D18-2S, and D18-3S)—each with different aerodynamic properties—in September 2018.[121] 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.[122]

17-hypersonic-missile/.

[113] *U.S.-China Economic and Security Review Commission 2018 Annual Report*, p. 235, at https://www.uscc.gov/sites/default/files/annual_reports/2018%20Annual%20Report%20to%20Congress.pdf.

[114] "Gliding missiles that fly faster than Mach 5 are coming," *The Economist*, April 6, 2019, at https://www.economist.com/science-and-technology/2019/04/06/gliding-missiles-that-fly-faster-than-mach-5-are-coming; and Franz-Stefan Gady, "China Tests New Weapon Capable of Breaching US Missile Defense Systems," *The Diplomat*, April 28, 2016, at https://thediplomat.com/2016/04/china-tests-new-weapon-capable-of-breaching-u-s-missile-defense-systems/.

[115] Department of Defense, *Military and Security Developments Involving the People's Republic of China 2021*, p. 60, at https://media.defense.gov/2021/Nov/03/2002885874/-1/-1/0/2021-CMPR-FINAL.PDF.

[116] Office of the Secretary of Defense, *Annual Report to Congress: Military and Security Developments Involving the People's Republic of China 2019,* May 2, 2019, p. 44, at https://media.defense.gov/2019/May/02/2002127082/-1/-1/1/2019_CHINA_MILITARY_POWER_REPORT.pdf.

[117] Jessie Yeung, "China claims to have successfully tested its first hypersonic aircraft," *CNN*, August 7, 2018, at https://www.cnn.com/2018/08/07/china/china-hypersonic-aircraft-intl/index.html.

[118] *U.S.-China Economic and Security Review Commission Report 2015*, p. 20.

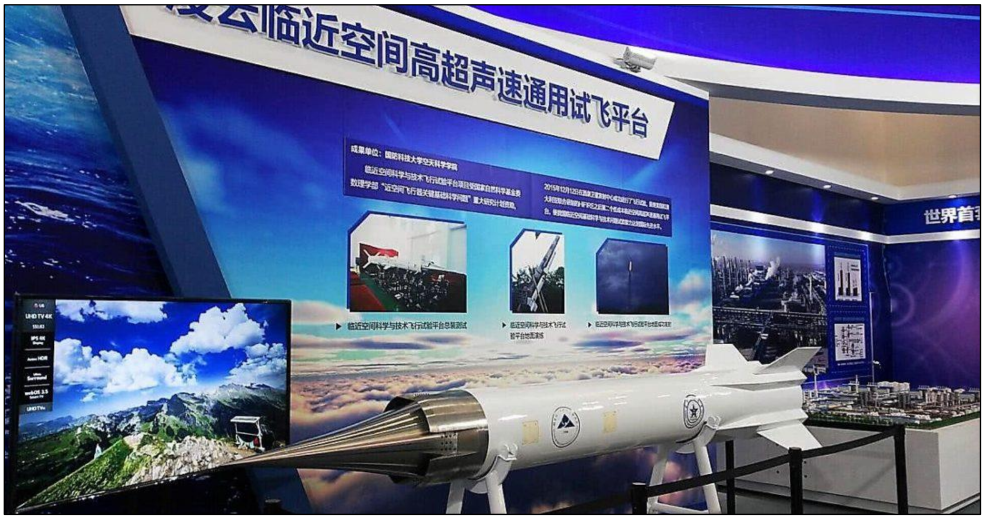
[119] Bill Gertz, "China Reveals Test of New Hypersonic Missile," *The Washington Free Beacon*, August 10, 2018, at https://freebeacon.com/national-security/chinas-reveals-test-new-hypersonic-missile/.

[120] *U.S.-China Economic and Security Review Commission Report 2015*, p. 20.

[121] Malcolm Claus and Andrew Tate, "Chinese hypersonic programme reflects regional priorities," *Jane's* (subscription required), March 12, 2019, at https://janes.ihs.com/Janes/Display/FG_1731069-JIR.

[122] Jeffrey Lin and P.W. Singer, "China's hypersonic military projects include spaceplanes and rail guns," *Popular Mechanics*, June 26, 2018, at https://www.popsci.com/chinas-hypersonic-work-speeds-up.

Figure 3. Lingyun-1 Hypersonic Cruise Missile Prototype



Source: Photo accompanying Drake Long, "China reveals Lingyun-1 hypersonic missile at National Science and Technology expo," *The Defense Post*, May 21, 2018.

According to *Jane's Defence Weekly*, "China is also investing heavily in hypersonic ground testing facilities."[123] 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.[124] China also operates the JF-12 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.[125] It will reportedly complete construction of the JF-22 wind tunnel, capable of reaching speeds of Mach 30, in 2022.[126] In addition, China is known to have tested hypersonic weapons at the Jiuquan Satellite Launch Center and the Taiyuan Satellite Launch Center.

[123] Andrew Tate, "China conducts further tests with hypersonic vehicles," *Jane's Defence Weekly* (subscription required), October 2, 2018, at https://customer.janes.com/DefenceWeekly/Display/FG_1120806-JDW.

[124] Kelvin Wong, "China claims successful test of hypersonic waverider," *Jane's* (subscription required), August 10, at 2018, https://janes.ihs.com/Janes/Display/FG_1002295-JDW; and Ellen Nakashima and Gerry Shih, "China builds advanced weapons systems using American chip technology," *Washington Post*, April 9, 2021.

[125] Jeffrey Lin and P.W. Singer, "A look at China's most exciting hypersonic aerospace programs," *Popular Science*, April 18, 2017, at https://www.popsci.com/chinas-hypersonic-technology.

[126] Andrew Tate, "China's new hypersonic wind tunnel expected to be ready next year," *Janes Defence Weekly* (subscription required), August 24, 2021, at https://www.janes.com/defence-news/news-detail/chinas-new-hypersonic-wind-tunnel-expected-to-be-ready-next-year.

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, South Korea, North Korea, 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.

In addition, South Korea reportedly has been developing a ground-launched Mach 6+ hypersonic cruise missile, Hycore, since 2018 and plans to test the missile in 2022. According to *Janes*, South Korea is developing the missile "in response to growing concern about North Korea military modernization" and plans to eventually develop sea- and air-launched variants.

Although North Korea tested the Hwasong-8—which it identifies as a hypersonic glide vehicle—in September 2021, reports indicate that the vehicle may have reached speeds of only Mach 3. Similarly, North Korea claims to have tested a second hypersonic weapon in January 2022; however, experts believe that that weapon may instead be a maneuvering reentry vehicle.

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. According to DOD, Japan and the United States have agreed to conduct "a joint analysis focused on future cooperation in counter-hypersonic technology."

Other countries—including Iran, Israel, and Brazil—have conducted foundational research on hypersonic airflows and propulsion systems, but may not be pursuing a hypersonic weapons capability at this time. In addition, a number of countries are testing increasingly maneuverable systems that travel at hypersonic speeds but that do not qualify as "hypersonic weapons" as defined in this report.

Note: For information about South Korea's hypersonic weapons programs, see Jon Grevatt and Rahul Udoshi, "South Korea develops Hycore hypersonic cruise missile," *Janes* (subscription required), January 25, 2022. For information about North Korea's hypersonic weapons programs, see Choi Soo-hyang, "N. Korea's 'hypersonic missile' appears to be at early stage of development: JCS," Yonhap News Agency, September 29, 2021; and Ankit Panda, "The real danger of North Korea's new hypersonic missile is not its speed," NK News, January 10, 2022. For information about Japan's hypersonic weapons programs, see Mike Yeo, "Japan unveils its hypersonic weapons plans," *Defense News*, March 14, 2020. For additional information about global hypersonic weapons programs, see Richard H. Speier et al., *Hypersonic Missile Proliferation*.

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, budget and management, 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.[127] 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."[128]

Given the lack of mission requirements, DOD officials have expressed a number of competing perspectives about the potential costs and intended quantities of U.S. hypersonic weapons. For example, Secretary of the Air Force Frank Kendall has stated that "hypersonics are not going to be cheap anytime soon ... [and thus] we're more likely to have relatively small inventories of [hypersonic missiles] than large ones."[129] Conversely, a number of other senior defense officials have stated that DOD intends to buy large quantities of hypersonic weapons. Then-DOD Director of Defense Research & Engineering Mark Lewis has noted that DOD wants "to deliver hypersonics at scale.... That means hundreds of weapons in a short period of time in the hands of the warfighter."[130] Similarly, Principal Director for Hypersonics Mike White has stated that DOD seeks to "[produce] hypersonics in mass, because you have to be able to deliver capability in meaningful numbers, even to defeat the high-end targets."[131] These perspectives appear to be grounded in differing assumptions about the affordability of hypersonic weapons. Likewise, they are likely to hold different implications for the unit cost of the weapons.

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 hypersonic weapons and alternative means of executing potential 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

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[127] Steve Trimble, "New Long-Term Pentagon Plan Boosts Hypersonics."

[128] Steve Trimble, "New Long-Term Pentagon Plan Boosts Hypersonics."

[129] John A. Tirpak, "Only Small Inventories of Hypersonic Missiles in USAF's Future, Due to Cost," *Air Force Magazine*, February 15, 2022, at https://www.airforcemag.com/only-small-inventories-of-hypersonic-missiles-in-usafs-future-due-to-cost/.

[130] Sydney J. Freedberg Jr., "Hypersonics: DoD Wants 'Hundreds of Weapons' ASAP," *Breaking Defense,* April 24, 2020, at https://breakingdefense.com/2020/04/hypersonics-dod-wants-hundreds-of-weapons-asap/.

[131] "Hypersonic Strike and Defense: A Conversation with Mike White," Center for Strategic and International Studies, June 10, 2021, at https://www.csis.org/analysis/hypersonic-strike-and-defense-conversation-mike-white. See also Jon Harper, "Just In: Pentagon to Spend Billions Mass-Producing Hypersonic Weapons," *National Defense Magazine*, March 4, 2020, at https://www.nationaldefensemagazine.org/articles/2020/3/4/pentagon-to-spend-billions-mass-producing-hypersonic-weapons.

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 Mike White has noted that DOD is prioritizing offensive programs while it determines "the path forward to get a robust defensive strategy."[132] This approach is reflected in DOD's recent budget requests. For example, DOD requested $225.5 million for hypersonic defense programs and $4.7 billion for hypersonic weapons programs in FY2023.[133] Similarly, in FY2022, DOD requested $247.9 million for hypersonic defense programs and $3.8 billion for hypersonic weapons programs.[134]

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."[135] 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.[136]

[132] Aaron Mehta, "Is the Pentagon Moving Quickly Enough on Hypersonic Defense?" *Defense News*, March 21, 2019, at https://www.defensenews.com/pentagon/2019/03/21/is-the-pentagon-moving-quickly-enough-on-hypersonic-defense/.

[133] Department of Defense Fiscal Year (FY) 2023 Budget Estimates, Missile Defense Agency Defense-Wide Justification Book Volume 2a of 5, p. 631, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol2_MDA_RDTE_PB23_Justification_Book.pdf; and *Defense Budget Overview: United States Department of Defense Fiscal Year 2023 Budget Request*, Office of the Under Secretary of Defense (Comptroller)/Chief Financial Officer, April 2022, p. 2-16, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/FY2023/FY2023_Budget_Request_Overview_Book.pdf.

[134] Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Missile Defense Agency Defense-Wide Justification Book Volume 2a of 5, p. 569, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2022/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol2_MDA_RDTE_PB22_Justification_Book.pdf; and *Defense Budget Overview: United States Department of Defense Fiscal Year 2022 Budget Request*, Office of the Under Secretary of Defense (Comptroller)/Chief Financial Officer, May 2021, p. 3-2, at https://comptroller.defense.gov/Portals/45/Documents/defbudget/FY2022/FY2022_Budget_Request_Overview_Book.pdf.

[135] "Department of Defense Appropriations Act, 2020: Joint Explanatory Statement," Defense Subcommittees of the Appropriations Committees, December 16, 2019, at https://appropriations.house.gov/sites/democrats.appropriations.house.gov/files/HR%201158%20-%20Division%20A%20-%20Defense%20SOM%20FY20.pdf.

[136] 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.

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).[137] 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.[138] 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."[139]

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.[140]

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.

Industrial Base and Supply Chain

U.S. government officials have expressed ongoing concern about the ability of the industrial base to support future demand for hypersonic weapons—particularly if multiple weapons programs go into production at the same time.[141] Indeed, a July 2022 DOD industry solicitation notes that "the expansion of industrial base capacity is *required*" [emphasis added] if DOD is to meet its goal of "[producing] the air-breathing engine constituent materials, subcomponents, components, and subsystems to support an initial integrated system production capacity of no less than 48 all-up-round (AUR) missiles (four to five units per month) and up to 72 AURs per year (six per month)."[142]

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[137] David Vergun, "DOD Awards Applied Hypersonics Contract to Texas A&M University," *DOD News*, October 26, 2020, at https://www.defense.gov/Explore/News/Article/Article/2394438/dod-awards-applied-hypersonics-contract-to-texas-am-university/.

[138] Ibid.

[139] Ibid.

[140] The Government Accountability Office notes DOD's difficulty in developing accurate cost estimates for hypersonic weapons programs. For example, between FY2019 and FY2020, estimates for CPS "almost doubled." Government Accountability Office, *Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts*, GAO-21-378, March 22, 2021, p. 21, at https://www.gao.gov/products/gao-21-378.

[141] See, for example, Justin Katz, "Hypersonics too expensive, industrial base too small for services to go it alone: Admiral," *Breaking Defense*, November 3, 2022, at https://breakingdefense.com/2022/11/hypersonics-too-expensive-industrial-base-too-small-for-services-to-go-it-alone-admiral/.

[142] Department of the Air Force, "Request for Information (RFI) on Supplier Based Initiative for Air-Breathing Engines for Hypersonic Systems," at https://www.businessdefense.gov/ai/dpat3/docs/AirBreathing%20Enginesfor%20HypersonicsRFFA8650225507.pdf.

Furthermore, a DOD report issued in response to Executive Order 14017 ("America's Supply Chains") recommends investments in the hypersonic industrial base.[143] The report notes that DOD is in the process of "developing a hypersonics industrial base roadmap to inform investments over the next five years, which will guide investment decisions over this period. The roadmap will address sub-tier supplier development, and where appropriate, develop and retain competition that enables affordable production."[144] The report additionally recommends that DOD "identify partners and allies with capabilities to aid in the development and expansion of [the U.S.] hypersonics supply chain, especially for materials and components where domestic sources may not exist."[145] Congress may wish to conduct oversight of DOD's efforts to strengthen the industrial base and supply chain for hypersonic weapons.

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."[146] 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.[147]

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."[148] 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.[149] Furthermore, these

[143] Department of Defense, *Securing Defense-Critical Supply Chains: An action plan developed in response to President Biden's Executive Order 14017*, February 2022, at https://media.defense.gov/2022/Feb/24/2002944158/-1/-1/1/DOD-EO-14017-REPORT-SECURING-DEFENSE-CRITICAL-SUPPLY-CHAINS.PDF.

[144] Ibid.

[145] Ibid.

[146] United Nations Office of Disarmament Affairs, *Hypersonic Weapons.*

[147] 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.

[148] Amy Mackinnon, "Russia's New Missiles Are Aimed at the U.S.," *Foreign Policy*, March 5, 2019, at https://foreignpolicy.com/2019/03/05/russias-new-missiles-are-aimed-at-you-weapons-hypersonic-putin-united-states-inf/.

[149] David Axe, "How the U.S. Is Quietly Winning the Hypersonic Arms Race," *The Daily Beast*, January 16, 2019, at https://www.thedailybeast.com/how-the-us-is-quietly-winning-the-hypersonic-arms-race. See also Mark B. Schneider, "Moscow's Development of Hypersonic Missiles," p. 14.

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 threating to use—not to mention to actually use—hypersonic weapons against the United States ... would end well."[150]

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.

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.[151]

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.[152] 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.[153] However, because New START is due to expire in 2026, this may be a short-term solution.[154]

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.[155] Other analysts have countered that a test

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[150] Jyri Raitasalo, "Hypersonic Weapons are No Game-Changer," *The National Interest*, January 5, 2019, at https://nationalinterest.org/blog/buzz/hypersonic-weapons-are-no-game-changer-40632.

[151] See United Nations Office of Disarmament Affairs, *Hypersonic Weapon*; and Richard H. Speier et al., *Hypersonic Missile Proliferation.*

[152] 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?"

[153] James Acton notes: "during [New START] negotiations, Russia argued that boost-glide weapons might constitute 'a new kind of strategic offensive arm,' in which case they would trigger bilateral discussions about whether and how they would be regulated by the treaty—a position [then] rejected by the United States." James M. Acton, *Silver Bullet?: Asking the Right Questions about Conventional Prompt Global Strike*, Carnegie Endowment for International Peace, 2013, p. 139, at https://carnegieendowment.org/files/cpgs.pdf.

[154] CRS Report R41219, *The New START Treaty: Central Limits and Key Provisions*, by Amy F. Woolf.

[155] Mark Gubrud, "Test Ban for Hypersonic Missiles?" Bulletin of the Atomic Scientists, August 6, 2015, at https://thebulletin.org/roundtable/test-ban-for-hypersonic-missiles/.

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."[156] 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."[157]

[156] Tong Zhao, "Test Ban for Hypersonic Missiles?"

[157] Rajaram Nagappa, "Test Ban for Hypersonic Missiles?"; see also James M. Acton, *Silver Bullet?*, pp. 134-138.

Appendix. U.S. Hypersonic Testing Infrastructure[158]

Table A-1. DOD Hypersonic Ground Test Facilities

Facility	Capability	Location
Air Force Arnold Engineering and Development Complex (AEDC) von Karman Gas Dynamics Facility Tunnels A/B/C	Tunnel A: 40-inch Mach 1.5-5.5; up to 290 °F Tunnel B: 50-inch Mach 6 and 8; up to 900 °F Tunnel C: 50-inch Mach 10; up to 1700 °F	Arnold AFB, TN
Air Force AEDC High-Enthalpy Aerothermal Test Arc-Heated Facilities H1, H2, H3	Simulate thermal and pressure environments at speeds of up to Mach 8	Arnold AFB, TN
Air Force AEDC Tunnel 9	59-inch Mach 7, 8,10, 14, and18; up to 2900 °F	White Oak, MD
Air Force AEDC Aerodynamic and Propulsion Test Unit	Mach 3.1-7.2; up to 1300 °F	Arnold AFB, TN
Air Force AEDC Aeroballistic Range G	Launches projectiles of up to 8 inches in diameter at speeds of up to Mach 20	Arnold AFB, TN
Holloman High Speed Test Track	59,971 ft. track; launches projectiles at speeds of up to Mach 8	Holloman AFB, NM
Air Force Research Laboratory (AFRL) Cells 18, 22	Mach 3-7	Wright-Patterson AFB, OH
AFRL Laser Hardened Materials Evaluation Laboratory (LHMEL)	High-temperature materials testing	Wright-Patterson AFB, OH
AFRL Mach 6 High Reynolds Number (Re) Facility	10-inch Mach 6	Wright-Patterson AFB, OH
Test Resource Management Center Hypersonic Aeropropulsion Clean Air Test-bed Facility	Up to Mach 8; up to 4040 °F	Arnold AFB, TN

Source: (U//FOUO) Paul F. Piscopo et al. Air Force AEDC Tunnel 9 was upgraded in 2019 to enable Mach 18 testing. See "Department of Defense Press Briefing on Hypersonics," March 2, 2020, at https://www.defense.gov/Newsroom/Transcripts/Transcript/Article/2101062/department-of-defense-press-briefing-on-hypersonics/.

158 The following information is largely 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. Additional information has been provided by Dee Howard Endowed Assistant Professor Dr. Christopher S. Combs (The University of Texas at San Antonio).

Table A-2. DOD Open-Air Ranges

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

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

Table A-3. DOD Mobile Assets

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

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

Table A-4. NASA Research-Related Facilities

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

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

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

Facility	Capability	Location
Sandia National Laboratories Solar Thermal Test Facility	High-temperature materials testing and aerodynamic heating simulation	Albuquerque, NM
Sandia National Laboratories Hypersonic Wind Tunnel	18-inch Mach 5, 8, and 14	Albuquerque, NM

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

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

Facility	Capability	Location
CUBRC Large Energy National Shock (LENS)-1/-II/-XX Tunnels	LENS I: Mach 6-22 LENS II: Mach 2-12 LENS XX: Atmospheric reentry simulation	Buffalo, NY
Boeing Polysonic Wind Tunnel	48-inch up to Mach 5	St. Louis, MO
Lockheed Martin High Speed Wind Tunnel	48-inch Mach .3-5	Dallas, TX
Boeing/Air Force Office of Scientific Research (AFOSR) Quiet Tunnel at Purdue University	9.5-inch Mach 6	West Lafayette, IN

Facility	Capability	Location
AFOSR-University of Notre Dame Quiet Tunnel	24-inch Mach 6	Notre Dame, IN
Stratolaunch Carrier Aircraft	Reusable Mach 6 test bed	Mojave, CA
University of Texas at San Antonio Hypersonic Ludwieg Tube	8-inch x 8-inch Mach 7.2	San Antonio, TX
University of Texas at Austin Blowdown Wind Tunnel	6-inch x 7-inch Mach 2 & Mach 5	Austin, TX
Southwest Research Light-Gas Gun	Quiet, flight enthalpy ballistic range up to Mach 20	San Antonio, TX
University of Texas at Arlington Aerodynamics Research Center	1.6 MW Mach 2-6 Arc Jet 13-inch Mach 4-16 Shock Tunnel	Arlington, TX
Texas A&M National Aerothermochemistry and Hypersonics Laboratory	7-inch Quiet Mach 6 36-inch Expansion Tunnel 9-inch x 14-inch variable Mach 5-8	College Station, TX
California Institute of Technology GALCIT	12-inch Mach 5.2 T5 Reflected Shock Tunnel 6-inch Hypervelocity (up to Mach 7.1) Expansion Tube	Pasadena, CA
University of Arizona Hypersonic Ludwieg Tube	15-inch Mach 5	Tucson, AZ
Air Force Academy Ludwieg Tube	20-inch Mach 6	Colorado Springs, CO
University of Tennessee Space Institute Ludwieg Tube	18-inch x 18-inch Mach 7	Tullahoma, TN
Maryland HyperTERP Reflected Shock Tunnel	12-inch x 12-inch Mach 6	College Park, MD
Florida State Polysonic Wind Tunnel	12-inch x 12-inch Mach 0.2-5	Tallahassee, FL
Princeton HyperBLaF Wind Tunnel	9-inch Mach 8	Princeton, NJ

Sources: (U//FOUO) Paul F. Piscopo et al.; Oriana Pawlyk, "Air Force Expanding Hypersonic Technology Testing"; and CRS correspondence with Dee Howard Endowed Assistant Professor Dr. Christopher S. Combs (The University of Texas at San Antonio), October 27, 2022.

Notes: Hypersonic wind tunnels are under construction at the following universities: Texas A&M University (Mach 10 quiet tunnel), Purdue University (Mach 8 quiet tunnel), and the University of Notre Dame (Mach 10 quiet tunnel). Additional universities, such as the University of Maryland, the Georgia Institute of Technology, and Virginia Polytechnic Institute and State University, also maintain experimental hypersonic facilities or conduct hypersonic research.

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