EMERGING TECHNOLOGIES INSTITUTE

HYPERSONICS SUPPLY CHAINS

SECURING THE PATH TO THE FUTURE

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EXECUTIVE SUMMARY

Over the past few years, the United States Department of Defense (DoD) has undertaken an ambitious effort to develop and deploy hypersonic technology in support of a variety of national security missions. Hypersonic weapons, are maneuverable, fly at least five times the speed of sound, or Mach 5, within the Earth's atmosphere, and can deliver long-range lethal effects on short time scales. Despite this recent effort, the DoD has often wavered in its commitment to fielding hypersonic systems at scale. Some years, it has been a clear priority while other times, the commitment has been ambiguous. As such, the current supply chains, including the manufacturing base, supply of critical materials, testing infrastructure, and workforce are incapable of supporting DoD's ambitious plans. That is not to say it is impossible, but instead, significant steps must be taken to strengthen hypersonics supply chains. To rectify critical hypersonics supply chains vulnerabilities, a holistic and coordinated approach among government, industry, and academia is essential. This integration will facilitate the cost-effective and reliable production of operational hypersonic systems. If action is taken now, the DoD's hypersonics aspirations are within reach. Listed below are the most important findings regarding hypersonics supply chain vulnerabilities and recommendations to address them.

Key Findings & Recommendations

- The most important step the DoD can take to secure hypersonics supply chains for the future is to provide a consistent demand signal to industry. During a series of industry working groups, business leaders have raised this issue time and again, illustrating the impact of uneven demand on every level of the supply chain. From the industry perspective, companies must know they will receive a return on investment. Industry is eager to invest in hypersonic technology, but the business case must exist for companies to invest in the necessary infrastructure and personnel.
- Hypersonic weapons require substantial quantities of critical raw materials and goods. Existing supply chains are unable to consistently provide the necessary access to these materials. Further investment is needed in the production and processing of high temperature materials such as carbon fiber and tantalum to ensure critical supply chains are able to meet rapidly expanding demand.
- The current hypersonic manufacturing base is insufficient to support fielding hypersonic systems at scale. The DoD should continue to pursue an air-breathing hypersonic vehicle system as a key element of its development plan to expedite manufacturing base growth and transfer critical knowledge from more senior hypersonic talent to new talent.
- In the short-term, academia should be leveraged for educating mid-level talent in hypersonic-adjacent fields to address workforce shortages. But in the long-term, academia needs to look for ways to provide students with hands-on hypersonic experience to prepare them to enter the workforce.
- The U.S. government should leverage existing international partnerships in hypersonics to secure supply chains. Most importantly, DoD should establish an overarching project agreement with Australia, a close ally and long-time partner on hypersonics. Existing agreements with Australia such as AUKUS and SCiFiRE provide a solid foundation, but to facilitate regular day-to-day partnerships, an overarching project agreement is important. The U.S. government should also look to Canada and Australia to diversify critical raw material supply, which currently relies heavily on China. Lastly, the U.S. should expand testing partnerships with Canada and Australia in order to address testing infrastructure shortages both in the short-term and long-term.

If implemented, the recommendations in this report will enhance the health and resilience of hypersonics supply chains for years to come.

INTRODUCTION

Over the past several years, the pandemic, subsequent economic challenges, and other world events have exposed the vulnerability and weakness of global supply chains. Nearly every sector has been affected, including defense and national security. However, the pandemic is not the only thing to blame for the disruptions. Winter storms, government policies, multiple natural disasters, and poor planning, among other factors, have illuminated an underinvested industrial base.

Within the defense sector, vulnerable supply chains are not uncommon. The U.S. government recognized the issue years ago and the last two presidential administrations have taken steps to try and address it through Executive Orders and reports.[1] Congress has also recognized the need for action. Early in 2021, the House Armed Services Committee launched a bipartisan Defense Critical Supply Chain Task Force and subsequently published a report outlining key findings.[2] Many nonprofits have also contributed to the effort, including the Hudson Institute's Hamilton Commission on Securing America's National Security Innovation Base, the Reagan Institute's Task Force on National Security and U.S. Manufacturing Competitiveness, and many others. This plethora of efforts – both inside government and outside – is indicative of the issue's importance.

One area that has received significantly less attention outside of government, however, is the nascent supply chains that will support advanced capabilities and emerging technologies as outlined in the 2018 and 2022 National Defense Strategies.

As such, the National Defense Industrial Association's nonpartisan think tank, the Emerging Technologies Institute (ETI) launched an in-depth research study focused specifically on defense emerging technology supply chains. The forward-focused study set out to assess the state of these supply chains and provide policy recommendations to advance their development, health, and resilience. The study is focused on key emerging technologies critical to the Department of Defense (DoD). As part of this study, this report will focus on hypersonic system supply chains.

The report focuses on four aspects of the hypersonics supply chains: 1) Critical Raw Materials and Goods, 2) Manufacturing Base and Workforce, 3) Supply Chain Security and Vulnerabilities, and 4) International Partnerships and Allied Nearshoring. While this report focuses on hypersonics supply chains, some issues raised are relevant to many different emerging technology supply chains.

WHAT IS A HYPERSONIC SYSTEM?

Both the 2018 and 2022 National Defense Strategies identify hypersonics as one of DoD's emerging technology priorities. While there is no fixed scientific definition of hypersonic systems, for the purposes of this report, they are defined are defined as maneuvering weapons that fly at speeds of at least Mach 5, five times the speed of sound, within the atmosphere. Hypersonics represent a wide range of systems, from jet-powered cruise missiles to large, high-speed gliders, and eventually aircraft and even launch vehicles. At the same time, hypersonic generally refers to the speed at which a weapon or craft must contend with very high surface temperatures, especially on leading edges, possible chemical reactions in the flow surrounding the vehicle, and strong shockwaves that are pressed close to the surface. The so-called boundary layer region of flow immediately adjacent to the vehicle is also hot and thick, which complicates sensing and can interfere with vehicle control and engine performance. Internal components must either be insulated or designed to operate at elevated temperatures. This means that hypersonic vehicles will require high temperature materials of many different types. Along with a plethora of unique components, hypersonic weapons incorporate many of the same components as more traditional weapon systems including sensors, guidance, navigation, control systems, and warheads. All components must be designed with the rigorous requirements associated with hypersonic flight in mind and these must all be considered when analyzing the supply chain.

As of this writing, each U.S. Military Service has an active hypersonic program, as does the Office of the Secretary of Defense via the Missile Defense Agency (MDA), the Space Development Agency (SDA), and Defense Advanced Research Projects Agency (DARPA). Efforts range from basic research to prototyping – aimed at rapidly deploying operational systems, including the U.S. Army's Long Range Hypersonic Weapon (LRHW), the Navy's Conventional Prompt Strike weapon (CPS) – to the Air Force's Hypersonic Attack Cruise Missiles (HACM). Both MDA and SDA are responsible for developing the U.S. hypersonic defense architecture. Though initial deployment numbers will be modest, plans exist to accelerate the ultimate delivery of hundreds, and eventually thousands, of hypersonic weapons.

As is evident in this report, these hypersonic systems have highly complex, and often opaque, supply chains. While this report does not claim to assess every single aspect of the hypersonic system supply chains, it does seek to identify critical vulnerabilities that must be addressed for the DoD to affordably field hypersonic weapons at scale in the years to come.

1 See Executive Order 13806 and subsequent DoD report "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States" (September 2018)
See Executive Order 14017 and subsequent DoD report "Securing Defense-Critical Supply Chains" (February 2022)

2 https://democrats-armedservices.house.gov/_cache/files/e/5/e5b9a98f-9923-47f6-a5b5-ccf77ebbb441/7E26814EA08F7F701B16D4C5FA37F043.defense-critical supply-chain-task-force-report.pdf

METHODOLOGY

The Emerging Technologies Institute (ETI) leveraged its unique position as part of the National Defense Industrial Association (NDIA) to conduct this Emerging Technologies Supply Chain Study. This position provided access to companies and industry experts at all tiers of the Defense Industrial Base (DIB), including academia, and allowed ETI to incorporate data and insight from those companies closest to the supply chain challenges. The methodology that ETI used is as follows.

First, ETI established a partnership with a NDIA academic member, the University of Maryland (UMD). This partnership culminated in a team of professors and graduate students from UMD's Supply Chain Management Center using open-source material to map hypersonics supply chains. UMD played a pivotal role in identifying lower-tier suppliers, sources of raw materials, and potential vulnerabilities that are analyzed throughout this report. Simultaneously, ETI convened 8 working groups comprised of 22 key stakeholders. Each working group met twice over the course of 2022 and focused on the four aspects of the supply chain listed in the introduction. The stakeholders were selected from industry, government, and academia based on their expertise and proximity to hypersonic systems and their relevant supply chains. ETI also conducted a number of interviews with other key stakeholders and subject matter experts. The working group findings were compiled into this final report along with the UMD research, data from interviews, and internal research. Prior to publication, this report was submitted to a peer review committee and several external reviewers with deep expertise in hypersonic systems. The peer review committee included former senior government officials as well as former and current industry officials, who each provided their expertise to strengthen the final product.

Early in the process, ETI decided to conduct the study at the unclassified level in order to provide a publicly releasable report to the widest audience possible. This limited the information that the research team could use, especially in Chapter 3. However, the ETI team deemed it more important that the information be widely accessible to all relevant stakeholders in industry, government, academia, and even foreign partners and allies for the recommendations to be implemented.

BACKGROUND

WHY ARE HYPERSONIC WEAPONS CRITICAL TO AMERICA'S NATIONAL SECURITY?

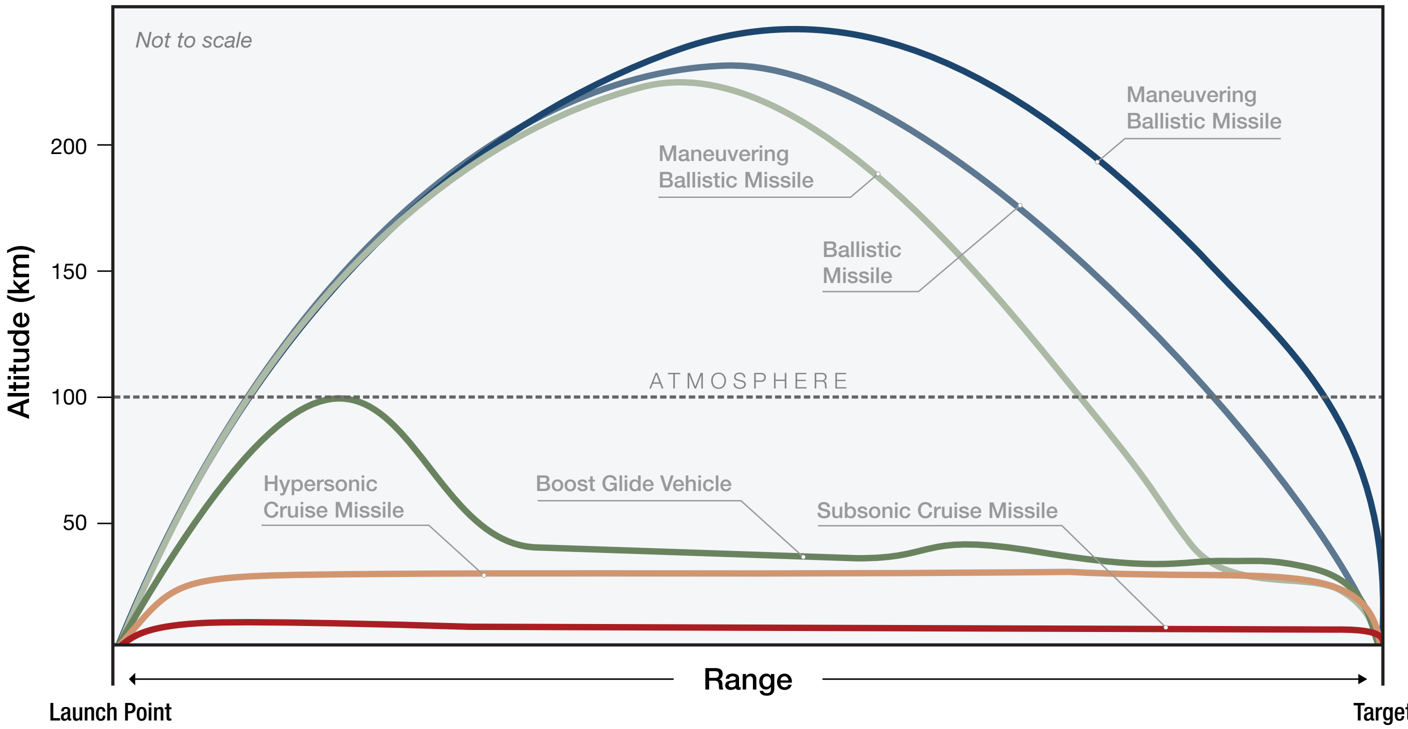
Hypersonic flight – flight in excess of five times the speed of sound – has a wide range of military applications. However, air-breathing cruise missiles and rocket-boost glide systems, both of which will be discussed in more detail below, are receiving the most attention and showing promise of being highly survivable, deep penetrating, rapid-response weapons. In the long term, reusable hypersonic craft could be used for intelligence, surveillance, and reconnaissance, as well as rapid delivery platforms and to supplement vulnerable space systems. Hypersonic flight technology can also be applied to very high-speed artillery projectiles, delivering high-impact kinetic energy at closing speeds of more than a mile per second.

Because of their speed, altitude, and maneuverability, hypersonic weapons provide numerous benefits. First, they could deliver long-range lethal effects on short time scales. If an adversary is launching missiles that take minutes to reach their target while U.S. missiles take hours, the U.S. is at a significant disadvantage. Speed limits vital decision time when determining how to respond to a threat, inhibiting an adversary's decision-making process. Perhaps the greatest advantage of having hypersonic weapons in the U.S. arsenal is to provide a non-nuclear option for quickly striking deep in enemy territory. At the same time, due to their unique characteristics, hypersonic systems are very challenging to detect and therefore, defend against. Prominent adversarial missile defense systems, including the Russian S-300 and Chinese HQ-22, were not designed to combat the advanced capabilities of hypersonic weapons.[1] A typical ballistic missile defense architecture uses intercept point prediction, which anticipates – based on previous flight characteristics – where that vehicle will be at the point of intercept. Because hypersonic systems often fly at altitudes well over 100,000 feet – an altitude approaching "near-space" – at extremely high speeds, the point of intercept becomes exponentially harder to ascertain.[2] Unlike ballistic missiles, hypersonic weapons fly below the line of sight of ground-based radars, limiting their detection vulnerabilities.[3] At the same time, hypersonic weapons can maneuver enough in-flight to offset the ability of kill vehicles to collide with an incoming warhead. Hypersonic weapons also pose a challenge to existing space-based sensor architecture, as they are 10 to 20 times dimmer than most weapons traditionally tracked by the existing architecture.[4]

Despite the significant advantages of hypersonic systems, the U.S. has historically waxed and waned in its investment in this promising technology. As the following report shows, this indecision has negatively impacted the hypersonics supply chains. However, the numerous current hypersonic programs within the DoD are promising – provided steady investment continues, promised technical progress is achieved, and systems are deployed quickly.

Currently, there are two competing technical approaches for hypersonic weapons: the airbreathing system and the rocket boost-glide system. Each has its own material requirements and technical challenges.

FIGURE 0.1: BOOST-GLIDE WEAPONS VS. BALLISTIC MISSILES VS. CRUISE MISSILES[5]



AIRBREATHING VS. ROCKET BOOST-GLIDE SYSTEMS

In an **airbreathing system**, commonly referred to as a Hypersonic Cruise Missile (HCM), the hypersonic vehicle is powered by a supersonic-combustion ramjet engine or "scramjet", a device that is deceptively simple in concept but difficult to design, test, build, and fly in actual practice.[6] As the vehicle flies through the atmosphere, air enters a front inlet, providing oxygen to burn with the fuel for propulsion. Since this system does not carry the oxidizer component of the combustion system onboard, it weighs less overall and can be smaller than those that use alternative methods of propulsion. The airbreathing system is also ideal for efficiently cruising long distances in the atmosphere. However, it does require significant technological investment in propulsion due to the complexity of the engines. Airbreathing hypersonics have a range of challenges, as ingesting air efficiently, injecting fuel into that air, mixing it, and burning it quickly are all difficult at hypersonic speeds. For higher speed systems in the future, fuel selection becomes a key element of the weapon design, and the ability to produce a given fuel will be a significant supply chain concern. Existing systems use readily available fuels but as hypersonic technologies advance and systems achieve higher speeds, unique fuel blends could become a significant supply chain issue.[7] The intense heat released inside a scramjet will require the use of either high temperature materials and/or active cooling, in which fuel is first circulated through the engine walls, absorbing heat and depositing it back into the combustor. Finally, extreme or sharp maneuvers can lead to malfunction due to the engine's sensitivity to airflow.[8]

With a **rocket boost-glide system**, commonly referred to as a Hypersonic Glide Vehicle (HGV), a hypersonic glider accelerates to high speeds on a rocket before separating and cruising through the atmosphere without power.[9] Such boost-gliders must be accelerated to higher Mach numbers than their jet-powered counterparts, so there is sufficient energy to bleed in cruise. As a result, they generally experience higher heat levels. However, this concept is beneficial for traveling longer distances and is often more maneuverable than airbreathing counterparts. It also has the advantage of using rockets, which utilize well-established supply chains and existing technology.[10] Current airbreathing cruise missile designs will fit within the bomb bays of existing U.S. Air Force bombers. However, unlike the airbreathing concept, the boost-glide system is less compact and must be carried outboard on an aircraft.

CURRENT U.S. DEPARTMENT OF DEFENSE HYPERSONIC PROGRAMS

The U.S. Department of Defense currently has at least 10 major unclassified offensive hypersonic programs, spread across the Services, Defense Advanced Research Projects Agency (DARPA), and the Office of the Undersecretary of Defense for Research and Engineering (OUSD (R&E)).

While U.S. investment in hypersonic systems has varied over the years, recent funding levels show some promise. While the DoD Comptroller officially requested $4.7B for offensive hypersonic weapons across all of the DoD, other program elements across the Research, Development, Test & Evaluation (RDT&E) title received an additional $1.07B in congressional earmarks for other Program Elements. This brings the entire topline FY23 (Fiscal Year 2023) DoD appropriation for hypersonics to nearly $6B.[11] Of the $4.7B, the RDT&E request was $2.896B and received $2.922B for named hypersonic programs.[12] Outside of the RDT&E title, DoD procurement requests related to directly named hypersonics efforts totaled $449M for FY23, up from $38.5M enacted in FY22.[13] In total, ETI found $3.31B across RDT&E and Procurement, indicating that the remainder of the Comptroller's cited $4.7B was distributed across other programs in RDT&E that are not specifically for hypersonic weapon systems, such as certain programs in Budget Activities 2 and 4 and the Operational Testing and Evaluation funding. The procurement requests were separated into three programs: 1) Long Range Hypersonic Weapon ($249M), 2) AGM-183A ARRW ($46.566M), and 3) Hypersonic Industrial Base funded through the Defense Production Act ($154M).[14] There are 46 Congressional earmarks across 21 program elements focused on hypersonic testing and evaluation and these are most heavily concentrated in Budget Activities 6.2, 6.3, and 6.6.[15]

The Navy CPS program, handled in close collaboration with the Army's LRHW, is to be installed on the "Zumwalt" DDG 1000 guided missile destroyer in FY24 following the removal of the current Advanced Gun Systems.[16] The Navy "is responsible for the design and development of the Common-Hypersonic Glide Body (C-HGB) and the missile booster; missile booster production; integration of the Army-produced C-HGB with the missile booster to create an all-up-round; and design, development, and production of the Navy's sea-based weapon control system and launcher."[17] Following initial installation and testing, the CPS hypersonic system will be fielded on the remaining two Zumwalt-class destroyers as well as Virginia-class nuclear submarines in FY25 and FY29 respectively.[18]

The first prototype battery of the LRHW, a land-based truck-launched system using technology developed in collaboration with CPS, is set to be fielded by the 5th Battalion, 3rd Field Artillery Regiment at Joint Base Lewis-McChord, Washington, in FY23, with second and third batteries fielded in FY25 and FY27, respectively.[19] Reportedly, each battery "is to have four Transporter Erector Launchers (TELs), each with two missiles, a mobile Battery Operations Center, and a number of support vehicles such as the Army's Heavy Expanded Mobility Tactical Truck (HEMTT) to transport the LRHWs."[20] There are plans for 66 missiles, including 48 development models.[21]

The Air Force's ARRW, an air-launched system that is based on the DARPA Tactical Boost Glide program and can be deployed from a B-52H bomber, had some success in early test flights and was expected to be the first American hypersonic weapon to achieve operational status.[22] However, after a failed test flight in March 2023, the Air Force announced its intention to shift focus to the development of the HACM system, leaving the future of ARRW in limbo.[23]

FIGURE 0.2: HYPERSONIC WEAPONS PROGRAMS

ORG/ SERVICE	PROGRAM	DESCRIPTION	RANGE	EST. INTRO INTO SERVICE
United States				
Navy	Conventional Prompt Strike (CPS)	Ship-Launched HGV	2775 km[24]	FY 2025[25]
Navy	Offensive Anti-Surface Warfare Increment 2 (OASuW Inc 2/HALO)	Air-Launched OASuW	Long-Range[26]	FY 2028[27]
Army	Long Range Hypersonic Weapon (LRHW)	Ground-Launched HGV	2775 km[28]	FY 2023[29]
Air Force	AGM-183 Air-Launched Rapid Response Weapon (ARRW)	Air-Launched HGV	1600 km[30]	N/A
Air Force	Hypersonic Attack Cruise Missile (HACM)	Air-Launched HCM	N/A	TBD (test and development to be completed by FY2027)[31]
Air Force	Southern Cross Integrated Flight Research Experiment (SCIFiRE)	Air-Launched HCM	N/A	TBD (demo tests expected by mid 2020s)[32]
DARPA	Tactical Boost Glide (TBG)	Air-Launched HGV	300 km[33]	N/A
DARPA	Operational Fires (OpFires)	Ground-Launched HGV	3000-5500 km[34]	TBD (integrated system critical design review was to be completed in 2022)[35]
DARPA	Hypersonic Air-breathing Weapon Concept (HAWC/MoHAWC)	Air-Launched HCM	483 km[36]	N/A
OUSD (R&E)	Hypersonics Flight Demonstration Program 2 (HyFly 2)	Air-Launched HCM	N/A	TBD (preliminary design review funded in FY 2021)[37]

The DoD is also developing several other hypersonic systems. Current estimates place OASuW's operational capability between FY28 and FY30.[38] Testing and development for the Hypersonic Attack Cruise Missile (HACM) builds on the DARPA Hypersonic Air-breathing Weapon Concept (HAWC) program.[39] As of this writing, the U.S. has conducted at least three successful hypersonic missile tests under the HAWC program, one successful test of DARPA's Operational Fires (OpFires), and demo tests of the SCIFiRE system will likely be seen by the mid 2020's.[40] Finally, the Joint Hypersonics Transition Office (JHTO) funded a preliminary design review and ground testing of the HyFly.[41]

The JHTO received $100M from Congress in FY20 and is charged with coordinating research and development activities in hypersonics. It also set up and oversees the University Consortium for Applied Hypersonics (UCAH). As of February 2023, the UCAH consists of 105 universities, including 10 international universities, 150 industry partners, and 17 University Affiliated Research Centers and Federally Funded Research and Development Centers.[42]

While the exact numbers are classified, the DoD has previously stated the goal of producing hundreds, and then thousands of hypersonic weapons.[43] While the above efforts by the U.S. government are a step in the right direction, they are still in the development phase and, as of this writing, the U.S. has yet to field a single hypersonic missile. If the U.S. is committed to incorporating hypersonic weapons into its arsenal at scale, an important question that must be answered today is: *what steps must be taken to ensure the hypersonics supply chains of the future are resilient and secure?*

FIGURE 0.3: CURRENT RUSSIAN & CHINESE HYPERSONIC PROGRAMS

PROGRAM	DESCRIPTION	RANGE	EST. INTRO INTO SERVICE
Russia			
Avangard	Ground-Launched HGV	6000 km[44]	FY 2019[45]
3M22 Tsirkon (Zircon)	Ship-Launched Missile	1000 km[46]	FY 2023[47]
KH-47M2 Kinzhal (Dagger)	Air-Launched Missile	2000 km[48]	FY 2018[49]
China			
DF-17 MRBM	Ground-Launched HGV	1931 km[50]	FY 2020[51]
Starry Sky-2 (XingKong-2)	Air-Launched HCM	800 km[52]	Mid 2020s[53]
Feitian-1	Ground-Launched Flight Vehicle (to deliver HGVs)	N/A	TBD (Successful test launch in FY 2022)[54]
ICBM-launched HGV	Ground-launched	Intercontinental	TBD (Successful test launch in FY21)[55]

Unlike the U.S., Russia and China have reportedly fielded operational hypersonic missiles. Russia claimed its maneuvering air-launched ballistic missile (the KH-47M2 Kinzhal) can carry a conventional or nuclear warhead and has been reported by Russian media to travel up to Mach 10.[56] The Kinzhal has been utilized throughout the conflict in Ukraine, although the missile may be experiencing a high rate of failure.[57] The Kinzhal's deployment marks the first time a hypersonic weapon has been used in combat. Russia is also developing two other hypersonic weapons programs, the Avangard and 3M22 Tsirkon. Avangard is a hypersonic boost-glide vehicle and has carried out several successful tests since 2014, reportedly achieving speeds as high as Mach 20.[58] The Tsirkon is a ship-and submarine-launched hypersonic missile and was allegedly deployed on the Russian frigate *Admiral Flota Sovetskogo Soyuza Gorshkov* for the first time in January 2023.[59] The Russian Navy has conducted several successful tests as recently as 2021, with the Tsirkon missile reaching approximately Mach 9.[60]

The total number of Chinese hypersonic programs is uncertain, but China has conducted successful tests on at least three as reported in open literature: the DF-ZF, Starry Sky-2, and Feitian-1. The DF-ZF is a hypersonic glide vehicle with at least nine tests since 2014 that can perform extreme maneuvers in flight.[61] Recent reports claim Chinese ballistic missiles can do the same, though details are minimal.[62] The Starry Sky-2 is a hypersonic cruise missile that can reportedly reach a top speed of Mach 6.[63] Uniquely, the Starry Sky-2 is a so-called "waverider" design that uses powered flight after launch and maximizes lift from its shockwaves.[64] Some reports indicate that the Starry Sky-2 could be operational by 2025.[65] The Feitian-1 is a ground-launched rocket that is allegedly the first-ever operational kerosene combined cycle ramjet/rocket engine capable of smooth transitions between at least three different propulsion configurations.[66] It is reportedly lighter than current boost-glide systems like the Air Force's ARRW and the engine enables it to operate efficiently during every phase of flight.

CHAPTER 1: CRITICAL RAW MATERIALS & GOODS

KEY ISSUES:

- High Temperature Materials
- Other Raw Materials and Goods
- Critical Mineral Market Trends

ASSESSMENT OF THE SECTOR[3]

The availability of critical raw materials and goods plays a vital role in U.S. defense supply chains, especially in the production of hypersonic systems. Current hypersonics supply chains face a plethora of vulnerabilities, including foreign dependency for sourcing. Although additional vulnerabilities may exist, this chapter will highlight those most pressing as well as provide recommended solutions to establish healthy and resilient hypersonics supply chains for the future.

3 Additional charts on mining and U.S. imports are available in Annex A

HIGH TEMPERATURE MATERIALS

High temperature materials have numerous applications in hypersonic systems including heat shields, thermal protection systems, rocket engine components, scramjet engine components, nozzles, and especially leading edges. The materials used for various high-temperature components include:

Carbon Fiber

Carbon fiber's physical and mechanical properties make it a preferred choice in the aerospace and defense industry. It is lightweight, durable, corrosion-resistant, chemical-resistant, and temperature-resistant. Carbon fiber is a key component of high temperature materials including carbon-carbon composites, silicon carbide, silicon carbon fiber, PICA (phenolic-impregnated carbon ablator), and ceramic matrix composites. Approximately 90% of all carbon fibers are manufactured using a policyacrylonitrile (PAN) process while the remaining 10% use a rayon or petroleum pitch process.[67] The U.S. and Japan are the top two carbon fiber producers.[68] With significant production occurring domestically and in an allied country, the carbon fiber supply chain is relatively healthy and secure. However, potential market shifts may introduce risk in the future.[69] According to a recent Market Research report, "The global carbon fiber market was valued at USD $6.5B in 2022 and is projected to reach $21.7B by 2032."[70] While there are numerous industries[71] that rely on carbon fiber, "aerospace and defense accounted for 44.2% in terms of value in the carbon fiber market in 2022."[72] The wind energy industry accounts for the second largest share at 14.7% of share in terms of value.[73] As countries impose strict environmental policies, the demand for carbon fiber (especially in the wind energy industry) will likely increase. According to recent estimates, with rapidly increasing demand, the carbon fiber market could see a potential shortfall of 55,250 metric tons by 2026.[74] Shortages in carbon fiber have existed in the past and suppliers have added additional capacity.[75] However, it can take a minimum of two years to construct and commission a new carbon fiber line.[76] With an increased emphasis by the government worldwide on alternative sources of energy, including wind, this could negatively impact the availability of carbon fiber, in the short-term, for aerospace and defense uses, including hypersonics.[77] At the same time though, in the long-term, growth of carbon fiber supply could benefit hypersonics supply chains. However, only time will tell if the carbon fiber industry can grow quickly and sufficiently to support all end uses including hypersonics.

Carbon-Carbon & Ceramic Matrix Composites

Carbon-carbon and ceramic matrix composites are lightweight, strong, and stiff materials that remain durable even at very high temperatures.[78] Carbon-carbon is the only option for coatings for the higher speed hypersonic systems. Because these composites have only niche applications and DoD demand is low, the supply base is relatively small, and most coatings are made by hand. According to industry participants in the working groups, there are only three suppliers for the carbon-carbon composites used in hypersonic vehicle coatings. The lack of a consistent market has led to a very fragile supply chain. Given these risks, some defense prime contractors are acquiring high temperature material manufacturers in order to guarantee availability.[79] DoD has taken notice of the fragile supply chain and is funding the University of Buffalo through LIFT, a DoD Manufacturing Institute to research alternate materials.[80] In December 2022, DoD also awarded $22.9M for expanded domestic production of high- and ultra-high temperature composites.[81] These are both steps in the right direction, but will likely take a significant amount of time to yield results. In the near-term, the current size of the supply base is a significant barrier to scaling hypersonic systems.

Tantalum

While tantalum has many other applications, it is an important component in tantalum carbide, an ultra-high temperature ceramic, with significant applications in hypersonic systems, given its high melting point (3880 C).[82] Tantalum powder also offers a highly corrosion-resistant, strong, and pure material. Its unique properties enable industry to 3D print components for aerospace and defense applications. Finally, tantalum is also used in manufacturing microelectronics which are found in hypersonic systems. There are three import streams of tantalum to the U.S.: 1) ores and concentrates,

2) metal and powder, 3) waste and scrap.[83] From 2018-2021, the U.S. imported most of its tantalum ores and concentrates from Australia (43%) and Rwanda (21%),[84] metal and powder from China (42%) and Germany (23%), and waste and scrap from Indonesia (23%) and China (17%).[85] Tantalum metal and powder is the product of processing ores and concentrates, which are then used to make alloys designed for different purposes. While tantalum is included in the National Defense Stockpile, thus providing limited insurance against supply issues in case of unexpected, increased demand, there is significant concern surrounding the percentage of U.S. tantalum metal and powder, and waste and scrap that originate from China. It is not clear from open-source information if tantalum for hypersonic uses is imported as ores and concentrates, metal and powder, or waste and scrap. Therefore, it is unclear how much risk is introduced into the supply chain due to reliance on China. If the majority of tantalum for hypersonic systems is imported as ores and concentrates, this supply chain is relatively secure and stable with reliance on a close U.S. ally. However, if the necessary tantalum quantities are imported as metal and powder or waste and scrap, Chinese production introduces significant risk into this aspect of the supply chain.

RARE EARTH ELEMENTS

The supply of Rare Earth Elements (REE), consisting of the 15 lanthanides on the periodic table plus scandium and yttrium, has been the subject of much discussion in the public forum over the past decade for applications that go far beyond hypersonics.[86] Although several rare earth elements have hypersonic applications, one of the most important is yttrium, a key component of ceramic applications including high temperature refractories for continuous-casting nozzles.[87] According to U.S. Geological Survey data, Chinese exports of refined rare-earth metals account for 74% of U.S. rare-earth imports from 2018-2021.[88] China not only mines the rare earth elements, but also controls more than 85% the world's processing capacity.[89] The only current domestic rare earths mining alternative to China is California's Mountain Pass mine, operated by MP Materials. In 2020, MP Materials extracted 38,503 tons of material,[90] compared to Chinese extraction reported at 140,000 tons in 2020.[91] However, MP Materials' raw material is sent to a subsidiary of the China-based firm, Shenghe Resources Holding Co. Ltd., for processing.[92] In 2021, Mountain Pass Mine in California received $10 million in funding from the Department of Defense to "help it build a $200M refinement facility for light rare earths."[93] With help from the DoD funding, processing for some light rare earths will be onshored, thus eliminating some reliance on China. At the same time, Round Top Mine in Texas, operated by USA Rare Earth, has similar goals to mine and process rare earths domestically. In 2020, USA Rare Earth opened a pilot processing facility in Wheat Ridge, CO with the goal of being "the first processing facility outside of China with the ability to separate the full range of rare earths."[94] While these recent developments are encouraging, mining and processing take time to reach full capacity. As such, the U.S. will continue to be reliant on China for REE mining and processing, thus posing a direct vulnerability to numerous defense and non-defense applications, including hypersonics.

OTHER RAW MATERIALS & GOODS

Ammonium Perchlorate

Until recently, the Department of Defense (DoD) relied on a single source for ammonium perchlorate (AP), a key component of hypersonic systems. AP is a principal raw material used in solid rocket propellants, and until recently, was sourced only from American Pacific (AMPAC). AMPAC was the only DoD-approved, North American supplier of the material since the company merged with Pacific Engineering and Production Company of Nevada in the 1980s.[95] The U.S. government actually assisted in consolidating the businesses following an industrial accident, the largest non-nuclear explosion in U.S. history at an AMPAC facility in 1988.[96] Advocates for the merger claimed it would drive down the cost of ammonium perchlorate due to economies of scale.[97] However, the second-order effects were significant vulnerabilities in the supply chain for solid rocket propellants with a single point of failure, higher prices due to lack of competition, and therefore a vulnerability for hypersonic systems. However, starting in 2016, Northrop Grumman (NG) stood up AP production for internal evaluation, increasing to full design production by 2019/2020.[98] NG's decision to begin producing AP at its location in Promontory, UT, was based on a desire to create competition in response to rising prices. NG is now a qualified supplier of AP to the U.S. government for multiple programs including hypersonic-related programs. Only time will tell if two AP suppliers for hypersonic purposes is sufficient. However, a second entrant into the market reduces the risks associated with a single supplier and will likely reduce costs, due to competition.

Cobalt

Cobalt is an integral component of Inconel-617 (an alloy of nickel, chromium, cobalt, molybdenum, and aluminum), which is used in hypersonic cruise missile engines due to increased strength and stability at high temperatures. Cobalt superalloys are also used in airframes. Finally, cobalt-chromium is a fine powder mixture superalloy characterized by excellent mechanical properties (strength, hardness, etc.), corrosion resistance, and temperature resistance, which is useful for hypersonic additive manufacturing applications.[99] With the total National Defense Stockpile reserve for cobalt and cobalt alloys at 666,144 lbs and 7,645 lbs respectively, there is limited insurance against supply issues in case of unexpected, increased demand.[100] However, with total U.S. cobalt consumption at 7,800 metric tons in 2022,[101] the stockpile would not last long. Additionally, three other market trends introduce risk into the cobalt supply chain.

First, there is a heavy reliance on the Democratic Republic of Congo (DRC) for production. The DRC is responsible for more than 70% of global cobalt production, thus there is potential for disruption due to regional volatility.[102] Over the past few years, China has also secured control of DRC's most valuable cobalt mines, with Chinese interests now owning 15 of 17 mines.[103] In 2018, Chinese companies controlled 24% of the total value of minerals and metals produced in the DRC.[104] Chinese companies focused on the DRC not only because of the mining production potential, but also because of reduced competition from other international companies due to reputational risks of operating in the DRC. Moreover, China is responsible for 65% of the refinement of cobalt.[105] Lastly, the potential surge in global demand for electric vehicle (EV) batteries could increase total cobalt demand this decade and beyond, increasing competition for cobalt until new mines are operational. According to the USGS, a new supply of cobalt is subject to developments in nickel and copper markets, as roughly 90% of cobalt is produced as a by-product of these minerals.[106]

Of note, these risks in the cobalt market may have less of an impact on the DoD, due to existing legal provisions. Under the "specialty metals clause" defense contractors and their suppliers are required to "purchase cobalt-base alloys and steel products - with greater than 0.25% cobalt - that is melted or produced in the U.S. or other close U.S. allies."[107] This clause, does therefore, provide "some protection for Defense Industrial Base-unique items"[108] but it does not apply to commercial products or electronics, among other items.[109] While these sourcing requirements might keep DoD from being reliant on foreign adversaries, they severely limit sources, thus introducing a different kind of risk into the supply chain. At the same time, the U.S. also imports 62% of its cobalt from key partners and allies including Norway, Canada, Japan, and Finland.[110] In conclusion, existing legal provisions and current import countries shield DoD and defense contractors from some of the risk in the cobalt supply chains. However, larger market shifts, as well as exceptions to the "specialty metals clause" and the second-order effects of the clause (limited sources), could potentially introduce risk impacting hypersonics supply chains in the future.

Aluminum

Aluminum has a plethora of defense and commercial applications and is critical for multiple parts of a hypersonic system. Aluminum is used in Inconel-617, an alloy with an exceptional combination of high-temperature strength and oxidation resistance. Inconel is an essential high temperature material that can be found in the airframes of both hypersonic cruise missiles (HCMs) and hypersonic glide vehicles (HGVs). Aluminum is also needed in Aluminum 7075, which is one of the most commonly used aluminum alloys for highly stressed structural applications.[111] Lightweight aluminum alloys are also used in additive manufacturing processes due to their high strength-to-weight ratios and resistance to metal fatigue and corrosion.[112] Though not a high-temperature material itself, aluminum is also needed for other parts of hypersonic weapons, including cruise missile fuel tanks and so-called cold structures.[113] Aluminum alloys, AlSi10Mg and AlSi12Mg, are typical casting alloys with good resistance in corrosive atmospheres as well as a high electrical conductivity, which suggests these alloys have application to some hypersonic craft.[114] Both alloys are also used for components that require a combination of good thermal properties and low weight.[115] Lastly, aluminum-based fuel-rich propellants have applications to hypersonic flight.[116] From 2018-2021, half of U.S. aluminum imports came from Canada.[117] During the same time period, only 5% of U.S. aluminum imports arrived from Russia and 4% came from China.[118] While China leads world aluminum smelter production (at 40,000,000 metric tons),[119] the U.S. primarily relies on a close U.S. ally, Canada, and maintains a small amount of domestic production (860,000 metric tons), thus limiting risk in hypersonics supply chains.[120]

Titanium

Titanium is a key material for both hypersonic cruise missiles (HCMs) and hypersonic glide vehicles (HGVs). With the ability to maintain strength at elevated temperatures, it is used in the airframe of HCMs and HGVs as well as the fuel tanks for HCMs.[121] Titanium alloy components are also essential for thermal protection systems.[122] Titanium Ti64 is a light alloy, ideal for many high-performance engineering applications, including aerospace additive manufacturing techniques.[123] Unalloyed, commercially pure titanium in grades 1- 4 is also used in additive manufacturing processes due to its extreme corrosion resistance, ductility, and weldability.[124] As of February 2021, the National Defense Stockpile contains 64,708 lbs of titanium alloys, thus bringing some short-term stability to the supply in a crisis scenario.[125]

There are two notable titanium supply chains: 1) titanium mineral concentrates and 2) titanium sponge. The three leading producers of titanium mineral concentrates are China, South Africa, and Mozambique.[126] Over half of U.S. imports are from South Africa (39%) and Australia (15%).[127] Titanium sponge is the product of processing raw titanium ore and is used as the base for titanium alloys, billets, and ingots among other parts. 89% of U.S. titanium sponge is imported from Japan.[128] In 2022, Japan was the second-largest producer of titanium sponge at an estimated 50,000 metric tons, while China is the global leader with an estimated 150,000 metric tons.[129] Russia is the third largest with 27,000 metric tons.[130] Despite China leading global production, the U.S. importing from partners and allies brings some security to what otherwise would be a vulnerable link in the hypersonics supply chains.

At the same time, the U.S. maintains some extremely limited domestic production; just 500 tons compared to 28,000 metric tons imported in 2022.[131] Other domestic facilities exist but have lain idle in recent years due to a number of factors including competition from cheaper imports and reduced demand due to the pandemic.[132] The U.S. is also reliant on one active foundry for the large titanium castings needed for key defense systems.[133] This vulnerability exists for several reasons, but "can be attributed in part to the impacts of offshoring and waves of industry consolidation since the mid-20th century."[134]

Overall, titanium is a relatively stable component in hypersonics supply chains, though vulnerabilities with castings do exist and domestic production has dropped significantly in recent years. Additionally, heavy foreign dependency does bring the potential for vulnerability, as the Covid-19 pandemic has shown in many different industries. In the long-term, the U.S. should consider the economic feasibility of restarting domestic production to eliminate the potential for disruptions and ensure stable, healthy, resilient hypersonics supply chains.

Nickel

Nickel is also a material found in Inconel-617, which is used in both the HCM and HGV airframe and thermal protection systems.[135] Nickel-based alloys (IN625, IN718, and Hastelloy X) and nickel aluminides are key high temperature materials needed to combat extreme heat during hypersonic flight. As such, they are commonly used in aero-based turbine engine parts and rocket components.[136] The nickel alloy inventory in the National Defense Stockpile currently stands at 1,343,550 lbs, as of February 2021.[137] Like cobalt, nickel may face higher demand in coming years, as high-nickel chemistries are the current dominant cathode for the electric vehicle (EV) market.[138] Currently, 45% of U.S. nickel imports come from Canada and so its supply therefore is fairly secure.[139] However, similar to other critical materials, China processes 35% of the global supply.[140] The next largest processor is Indonesia (with 10%) which also accounts for 25% of total nickel extraction.[141] According to the International Energy Agency, Chinese production becomes even higher when including the involvement of Chinese-owned companies with Indonesian operations.[142] Overall, because the U.S. primarily imports nickel from a close ally, Canada, this link in hypersonics supply chains is relatively stable. However, with changing markets and Chinese dominated processing, future supply could require attention.

Neon & C4F6

Many critical raw material vulnerabilities impact both hypersonic systems as well as other emerging technology supply chains. For example, neon is an essential element used in the fabrication of semiconductor chips. While not found in the chips themselves, neon is used in the lasers required during the lithography process and must be exceptionally pure.[143] Ukraine is responsible for approximately 50% of the global supply of neon.[144] More than 90% of neon for U.S. semiconductors is sourced from two Ukrainian companies – Ingas and Cryoin.[145] Ingas is responsible for 54% of the world's neon supply and is based in Mariupol while Cryoin is responsible for 45% of the world's neon supply and is based in Odessa.[146] During the 2014 Russian occupation of Crimea, neon prices reportedly spiked over 600%.[147] The 2022 Russian invasion of Ukraine has again put the supply of neon in jeopardy.[148] Neon is produced as a byproduct of Russian steel manufacturing, which Ukraine has previously sourced and purified. As of writing, Russian exports to Ukraine have been impacted, due to the war, and the top two gas purifiers have stopped production.[149] While major semiconductor industry companies have multiple sources of neon gas supply, the war in Ukraine has severely limited one primary source, thus revealing a significant vulnerability in semiconductor supply chains.[150] The war in Ukraine has also put a strain on the supply of C4F6 – a chemical gas compound critical in the etching process for chip production primarily sourced from Russia.[151] U.S. dependency on Russian materials critical for semiconductor production could worsen if Moscow withholds exports as a response to economic sanctions.

Plastics

Plastics are integral to additive manufacturing technology, with a few notable plastics that are especially relevant to the hypersonics supply chains. Acrylonitrile Butadiene Styrene (ABS)-M30 is characterized by its strength and toughness, while being lightweight and resilient.[152] ABSi offers superior strength compared to standard ABS, making it an ideal material for conceptual modeling and functional prototyping.[153] Nylon, or Polyamide (Pa) is a commonly used polymer which yields components that are robust, chemically resistant, and versatile.[154] Polycarbonate is a lightweight, yet strong thermoplastic and known for its impact resistance.[155] While these materials are used in models and prototypes. and are not planned for use in production systems, shortages of these materials could impact upgrades and future generations of hypersonic systems. Because these materials are petroleum-based, impacts in that market will affect plastics integral to additive manufacturing. Due to several different factors over the past few years, plastic markets are facing supply disruption. According to a 2021 article in the *Harvard Business Review*, "constraints on the supplies of... raw materials - especially polyethylene (PE), polypropylene (PP), and monoethylene (MEG) - are leading to factory shutdowns, sharp price increase, and production delays across a range of industries."[156] While these disruptions seem bleak, it is likely that with time, the market will bounce back and the impact on future hypersonics supply chains will be limited.

FIGURE 1.1: CRITICAL MATERIALS RISK ASSESSMENT[4]

Materials	Top Producers	Vulnerability	Explanation
Tantalum	Congo, Brazil, Rwanda		Ores and concentrates sourced from ally, but metal and powder sourced from China.
Rare Earths	China, U.S., Australia		China dominates mining and processing
Cobalt	Congo, Indonesia, Russia		U.S. imports from partners/allies, despite China dominating processing
Aluminum	China, India, Russia		Half of U.S. imports are from an ally
Titanium	China, Mozambique, South Africa		Over half of U.S. imports are from partners or allies
Nickel	Indonesia, Philippines, Russia		U.S. imports from allies despite China dominating processing
Carbon Fiber	Japan, U.S.		Demand may outpace supply in the near-term
Ammonium Perchlorate	China		Only two DoD-approved suppliers
Carbon-Carbon	Japan, China, U.S.		Only three available suppliers, and manufacturing & distribution is expensive
Neon and C4F6	Ukraine (Neon); Japan, South Korea (C4F6)		War in Ukraine disrupted supply but major companies have multiple suppliers
Plastics (ABS–M30, ABSi, Nylon, Polycarbonate)	South Korea, U.S., Germany, China, Japan		Short-term disruptions, but market will likely rebound long-term

CRITICAL MINERAL MARKET TRENDS

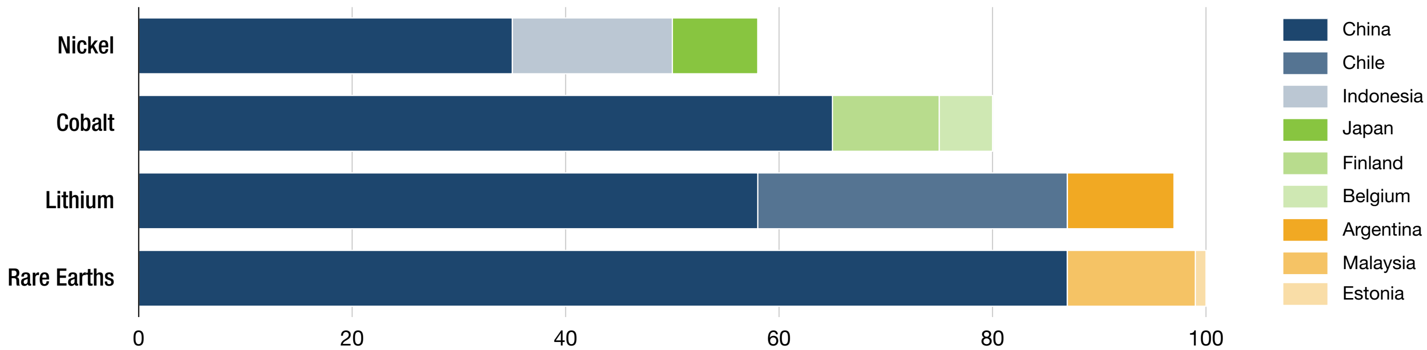
Major economic shifts in other sectors that rely on the same critical raw materials as hypersonics can also impact these supply chains. According to the International Energy Agency (IEA), global renewable electricity capacity is projected to increase more than 60% by 2026.[157] The potential emergence of a new global energy economy due to stricter policies from many countries will have numerous secondary effects. As economies attempt to transition to alternative forms of energy, they must be proactive in acquiring the necessary critical minerals to meet the growing demand. For example, a standard electric vehicle (EV) requires six times the mineral inputs of a conventional car and an onshore wind plant requires nine times more mineral resources than a gas-fired plant.[158]

While the types of mineral resources needed vary by technology, the Biden administration's goal of the U.S. economy reaching net zero CO_2 emissions by 2050 will dramatically increase competition for key minerals.[159] Lithium, nickel, cobalt, manganese, and graphite are fundamental to battery performance, longevity, and energy density. Rare earth elements are essential for permanent magnets that are crucial for wind turbines, EV motors, and some defense applications. Electricity networks require copper and aluminum, with copper functioning as a cornerstone for all electricity-related technologies.[160]

This shift has also revealed and increased an alarming reliance on China, especially in processing many of the necessary critical minerals. As shown by Figure 1.2, China dominates processing of nickel, cobalt, lithium, and rare earths.[161] In addition to a dangerous reliance on China, this shift to alternative forms of energy will likely result in a serious supply crunch of minerals needed for electric products, which could leave the hypersonics industry at a disadvantage.[162] In the near-term, some minerals such as mined lithium and cobalt are expected to be in surplus; however battery-grade nickel and key rare earth elements are estimated to be in tight supply.[163] While new mining projects are underway, the IEA assesses it takes on average over 16 years to move mining projects from discovery to first production.[164] Thus,

4 This chart is a visual representation of the information and data in Chapter 1. Green generally represents a healthy mix of domestic producers and/or imports from allies and partners. Yellow represents some level of vulnerability due to factors such as limited suppliers, disrupted supply, etc. Red represents clear, significant vulnerabilities. Vulnerability designation was determined based on the following factors:
Does mining and/or processing occur in China (or under Chinese control)? (negative)
Does mining and/or processing occur in Russia (or under Russian control)? (negative)
Does mining and/or processing occur in a volatile region? (negative)
Does mining and/or processing occur in a stable region and is controlled by a US ally or partner? (generally positive)
Does the US import from a stable region? (positive)
Does the US import from an ally or partner? (positive)
Is the US the largest producer? (positive)
If the US is not the largest producer, does the US produce enough domestically to meet demand? (positive)
Are there significant market shifts occurring or are likely to occur? (negative or positive depending on context)

FIGURE 1.2: TOP 3 ELEMENT PROCESSING COUNTRIES



in the near-term, the energy transition may introduce further risk to the affordability and availability of critical minerals for hypersonics. In the long-term however, these market changes could possibly serve to drive the delivery cost of critical minerals down for various end-uses, including hypersonics. Overall, how companies and policymakers respond will determine whether the clean energy market will form a bottleneck, or if the future supply of critical minerals can affordably meet the needs of both the hypersonic and energy markets.

SUMMARY

Critical raw materials and goods in hypersonics supply chains face several challenges, including foreign source reliance and shortages due to the pandemic and other factors. While some pose significant vulnerabilities in the hypersonics supply chains, like rare earth elements, others, like plastics, face short-term challenges that may be righted by economic forces over time. In some cases where there is a challenge for future supply, industry and the DoD have begun to look for alternatives but these efforts needs to be expanded and fully resourced. Of the materials discussed in this chapter, high-temperature materials and the raw materials necessary for them are the most critical. The following recommendations should be implemented to ensure secure hypersonics supply chains in the future.

RECOMMENDATIONS

1. Working together, Congress and the Department of Defense should reinforce the National Defense Stockpile of strategic minerals.

The U.S. National Defense Stockpile has diminished over the years, particularly following the end of the Cold War.[165] This reduction included several million pounds of materials necessary for hypersonics manufacturing.[166] The stockpile is currently valued at less than $1B, which is roughly 1/40th of its value in 1952 when adjusted for inflation.[167] This potentially increases U.S. dependence on Chinese reserves, as well as their mining operations in developing countries, in times of unexpected, increased demand. Funds for maintaining the stockpile are also nearly depleted, with the program expected to exhaust its money by FY25.[168] Congress should conduct a review of the National Defense Stockpile alongside the DoD, and based on the results, appropriate additional funding to quickly replenish and maintain critical materials. It is equally important to verify that the Defense Logistics Agency Strategic Materials organization is sufficiently staffed and has the necessary core competencies to ensure sustainment. Finally, once the stockpile is restored to adequate levels, the U.S. government must ensure that critical resources are not sold off due to a perceived lack of critical need. The war in Ukraine has demonstrated that strategic resources can be rapidly consumed in a crisis and must be maintained. Even if there is no immediate utility, the security needs of the future must be prioritized. By fortifying the current stockpile of rare earth minerals and other critical materials, especially carbon fiber and metals needed for high temperature materials, DoD supply chains can better meet the demands of today's great power competition without relying on China or other adversarial countries.

2. DoD should provide a clear demand signal to private industry to increase investment in additional carbon fiber suppliers.

Due to increased demand across multiple sectors, additional capacity is needed in the carbon fiber manufacturing industry. Although hypersonics is just one slice of demand for carbon fiber, increases in supply overall will support healthier hypersonics supply chains. However, it can take a minimum of two years for a facility to fully function. Thus, investment must be made today to support the supply chains of the future. A consistent demand signal from the government down through the tiers of the supply chain will help convince investors of a long-term return on investment. To effectively communicate this demand signal to carbon fiber suppliers, the DoD could deploy representatives to aerospace events to emphasize the rapid expansion of carbon fiber demand within the defense sector and the increasingly vital role this material plays in U.S. national security. These demand signals, combined with existing knowledge on the rapid expansion of carbon fiber demand in the wind, aerospace/defense, and infrastructure sectors, should give carbon fiber suppliers additional confidence in the merits of expanded production.

3. Through significant reform, the U.S. government should set the regulatory environment to permit and incentivize more domestic rare earth mining and processing.

Mining is currently one of the most heavily regulated industries in the world, presenting many potential obstacles to obtaining the rare earth elements necessary to ensure effective hypersonics supply chains. While some degree of regulation is warranted, more than three dozen federal environmental laws and regulations govern the U.S. mining industry, not to mention additional laws at the state and local levels.[169] Cumbersome and lengthy permit processes have already hampered the necessary and critical domestic development of potential rare earth mines. For example, the enormously promising rare earth deposit in the Bear Lodge mountains of Wyoming is estimated to hold 18 million tons of rare earth materials.[170] A delay in mining occurred despite Colorado-based Rare Earth Resources providing ample amounts of environmental data. If the U.S. government truly wants to diversify the supply of critical raw materials, especially those necessary for hypersonic systems, and consider domestic mining or processing for certain materials, this complex regulatory environment should be appropriately reformed, better balancing the needs of the environmental, defense, and manufacturing communities. By initiating targeted regulatory reform, the U.S. government will enable the rare earth industry to function more effectively, thereby facilitating a reliable domestic source of rare earth materials for a variety of applications, including hypersonic systems.

4. Industry should expand partnerships with both government and academia to incorporate new innovative rare earth extraction and processing methods, once shown to be effective and economical.

While the U.S. was once the leading REE producer, the increase in environmental regulations and higher production costs led to much of the industry migrating to China due to its lax environmental laws and cheaper production costs. This shift has substantially compromised America's ability to guarantee access to many REEs that are vital to its hypersonics supply chains. Recently, there has been a renewed push to develop a cleaner domestic rare earth industry capable of encompassing the entire rare earth supply chain. Some progress has been made in recent years and the government has increased R&D funding on various projects. For example, researchers are developing methods for extracting REEs using bacteria rather than toxic chemicals, and researchers at Purdue University have developed a method of extracting REEs from coal ash instead of mining for ores.[171] Additionally, newly identified ligands (organic molecules with a thirst for metal atoms) have enabled existing solution-based methods to become increasingly efficient, generating substantially less toxic waste than in years past.[172] While these developments are encouraging, much more work remains if the U.S. is to diminish reliance on China for rare earth element mining and processing. In order to maintain and expand on this progress, it is essential that industry begins to partner with academia and government. Only by moving these methods from the lab into industry will real impact occur. Once these technologies are proven to be effective and economically feasible, industry should move to incorporate them into its mining and processing procedures.

CHAPTER 2: MANUFACTURING BASE & WORKFORCE

KEY ISSUES:

- Manufacturing Base
  - Insufficient Manufacturing Base Due To Inconsistent Demand Signal
  - Limited Suppliers
  - Advanced Manufacturing
  - Casting And Forging
  - Unit Cost
  - Long Lead Times
  - Data Sharing & Storage
  - Testing Infrastructure
- Workforce
  - Lack Of Hypersonic Talent
  - Clearance Process Stymies Development Of Needed Workforce
  - Increased Strain On Testing Facility Personnel

ASSESSMENT OF THE SECTOR

The U.S. manufacturing base and workforce is essential to the DIB's ability to develop and deliver hypersonic capabilities at scale. While not traditionally considered part of a supply chain, testing infrastructure is a key component of delivering hypersonic systems and therefore was also considered by the working groups. During the ETI-led working groups, participants assessed the health of the current manufacturing base and workforce by addressing key issues, areas of success, and opportunities for improvement through policy changes. Overall, the existing hypersonic manufacturing base and testing infrastructure is insufficient to meet the needs of the future. At the same time, the accompanying hypersonic workforce has waned over the years and cannot meet the current, much less, future demands. Over the past few years, some positive steps have been taken, however, it is not enough.

MANUFACTURING BASE

Insufficient Manufacturing Base Due To Inconsistent Demand Signal

Throughout the hypersonic working group discussions, a common theme from industry and academia was a lack of consistent government demand signal when it comes to hypersonics. As such, the existing manufacturing base is small and suited only to manufacturing small numbers of hypersonic systems with long lead times. In recent years, DoD leadership has attempted to send a clearer demand signal for hypersonic systems by stating the need for "hundreds in a short period of time" and according to one official, potentially even thousands or tens of thousands.[173] This, in theory, would be a tremendous leap from the current demand for a handful of prototypes, if supported by budget requests and appropriations. The current manufacturing base cannot produce hypersonic systems at that scale due to several issues that will be addressed in this chapter. Solutions are also presented but must be implemented quickly to create secure, resilient supply chains to supply hypersonic systems at scale.

Limited Suppliers

According to a number of working group participants, the hypersonic manufacturing base relies on a relatively limited supply base. As noted in chapter 1, many materials used in hypersonic systems are highly specialized and do not have extensive commercial applications, which limits the number of companies participating in the market. For example, there are only two U.S. suppliers of rocket motors used in missile propulsion systems: Aerojet Rocketdyne and Orbital ATK. Orbital ATK was acquired by Northrop Grumman in 2018, while Aerojet Rocketdyne is set to be acquired by L3 Harris Technologies in 2023, pending government approval.[174] As prime defense contractors depend on propulsion system components for hypersonic vehicles, reliance on only two entities may be driving costs up (due to a lack of competition) and creating a potential point of failure in the supply chain. Hypersonic systems are only a small percentage of the rocket motor market, with the space industry making up the majority. As the proliferation of space continues to take off, this will put increased demand on an already limited supply, potentially channeling finite resources away from hypersonics development. According to one industry participant, limited supplier issues also exist with hypersonic structural components like TZM (Titanium-Zirconium-Molybdenum) bolts that are used to provide strength at elevated temperatures, as well as protective items such as thermal blankets that shield the vehicle from excessive heat. Because the commercial market is almost nonexistent for these materials, the industrial base remains small, and the market remains fragile due to inconsistent demand. Finally, due to the limited number of second and third-tier suppliers for critical hypersonics components, prime defense contractors often share vendors. For example, Lockheed Martin and Raytheon are both reliant on the same suppliers for radar equipment, propulsion systems, satellite electronics, and semiconductor chips. This creates a potential vulnerability in supplier overlap and limited suppliers.

As discussed in Chapter 1, there is a limited supply base for high temperature materials. This need, in particular, has been recognized and Purdue University's Hypersonics Advanced Manufacturing Technology Center (HAMTC) is currently heading an effort with several leading defense contractors to produce high-temperature materials necessary for hypersonic flight. Research in advanced manufacturing capabilities will play a vital role in the study of these materials, but the effort cannot stop there. Both industry and government need to consider more investment in these alternative production techniques for improving the technological capability needed for tomorrow's hypersonic systems.

Advanced Manufacturing

Advanced manufacturing, and in particular additive manufacturing (AM), has the potential to enable industry to cost-effectively increase production. According to the Deputy Director of the Office of the Secretary of Defense's Manufacturing Technology Program, "The science has proven it's possible, but the practice is not widespread enough."[175] The hypersonic industry has already seen significant improvements in weapon design and cost reduction, through AM. According to two industry participants, AM has resulted in 20 times the reduction in the number of components required when compared to the X-51. This progress is paramount to the scaling of hypersonic weapons, as decreasing the number of parts also reduces the number of potential failure points. According to the same industry participants, the subsequent effect is an 8-fold decrease in cost accompanied by the part reduction and a 4.5-fold reduction in lead time for components.

As a general practice, AM is not a blanket application. However, some hypersonic systems require intricate geometric specifications that traditional manufacturing processes are unable to meet or are too expensive to produce at scale. This has led DoD to request prototype solutions for its Growing Additive Manufacturing Maturity for Airbreathing Hypersonics (GAMMA-H) challenge.[176] The objective is for AM companies to address propulsion and high temperature requirements for systems traveling at Mach 5 or higher.

These benefits not only improve the performance of the weapon, but also drive the justification for companies to invest in AM. While AM will disproportionately affect air-breathing systems, there are multiple areas of hypersonic weapon design that lend themselves best to new manufacturing techniques. These include liquid rocket motors that use a fuel-cooled design. AM can improve both the thermal performance of the engine as well as the overall performance. Ultimately, reducing the cost of the engine and advancing its performance is critical for scaling up production. Design flexibility is also suitable for highly complex components, such as heat exchangers, optimized topologies, or complex cooling channels. Finally, AM could be used for wiring, antennae, and circuit boards in order to reduce weight, according to an industry participant.

Overall, AM reduces the number of components and people involved in the manufacturing process and eliminates tooling. For design complexity, AM achieves a performance that cannot be accomplished with conventional techniques. Advanced manufacturing also includes new technologies, such as big data collection, simulation software, and machine learning, which monitor AM processes by predicting stress and part distortion. The convergence of modern technologies advances hypersonic technology by removing welding, unnecessary machine operations, and joints. However, when considering where AM techniques can be applied, it should be noted that the materials needed ought to exist in sufficient quantities either through domestic or allied sources. Nevertheless, this improvement in manufacturing methods can substantially improve lead time and cost overall for hypersonic systems.

Casting & Forging

Limits to current domestic casting and forging (C&F) capability and capacity continue to be a key challenge for DoD, including hypersonics development. Castings are high-temperature composites or metals poured into complex shapes, while forgings are made by hammering or squeezing metal until it reaches its maximum density and strength. As one of the five priority sectors noted by the Defense Department in the "Securing Defense-Critical Supply Chains" report, castings and forgings are critical for all major defense systems as they are "essential components of the machine tools and other equipment used to produce and sustain [those] systems."[177] Forging capacity was also raised as an issue by an industry working group participant.

Since the 1970s, the C&F industry has faced major consolidation due to intense global competition, technological changes, and environmental and economic factors.[178] The U.S. C&F industry faces challenges in aging infrastructure, limited capacity and capability, and workforce. Comparatively, China produced four times the amount of casting tonnage as the U.S. in 2019 and remains the world's leading producer of casted products.[179] Within defense, the C&F industry reports issues with non-standard technical data packages, complex contracting processes, burdensome accounting system requirements, small and unreliable demand, and slow procurement practices.[180] Fewer U.S. and allied companies can afford to improve their manufacturing equipment or processes. This, in turn, creates long lead times, as industry waits for these specialized materials. In fact, DoD reports that it currently relies on foreign countries, including China, for very large cast and forged products used in some defense systems and many machine tools and manufacturing systems.[181]

The U.S. military is working with the C&F industry to address these issues through investments in C&F firms, the creation of a Forging Defense Manufacturing Consortium (FDMC), and a C&F strategy that is expected to be published no later than the end of

Q2 of FY23.[182] There are similar efforts being made by the U.S. Department of Energy (DoE) through the creation of the Advanced Manufacturing Office (AMO). A DoE-funded study outlined four additive manufacturing technologies with applications in the forging industry: Laser-based Powder Bed Additive, Metal Binder Jetting, Sheet Lamination, and Directed Energy Deposition.[183] One industry working group participant noted that powder bed fusion's ability to mix and match elements will be extremely helpful for the hypersonics industry.[184] More specifically, the C&F industry is looking into a number of AM methods and processes, including: AM in valve production, custom forging, additive friction stir deposition forging, and Powder Metallurgy AM.[185] Overall, AM can help with the unique properties needed from forging. Another technical advancement that could improve the C&F industry – and by extension hypersonics – is digital engineering. However, the Forging Industrial Association reported 34% of forging companies in 2020 – within their membership – do not use computer simulation in the design or analysis of their forging process, citing reasons listed in Figure 2.1.[186]

Overall, the growth of the aerospace industry represents an opportunity for investment. According to a 2020 survey, aircraft/aerospace components were considered the market area with the most promise for forging companies (Figure 2.2).[187] With hypersonics as a sub-category of aerospace, forging companies should take advantage of this opportunity and therefore satisfy the needs of the C&F industry and DoD.

FIGURE 2.1: REASONS FOR NOT USING FORGING COMPUTER SIMULATION[188]

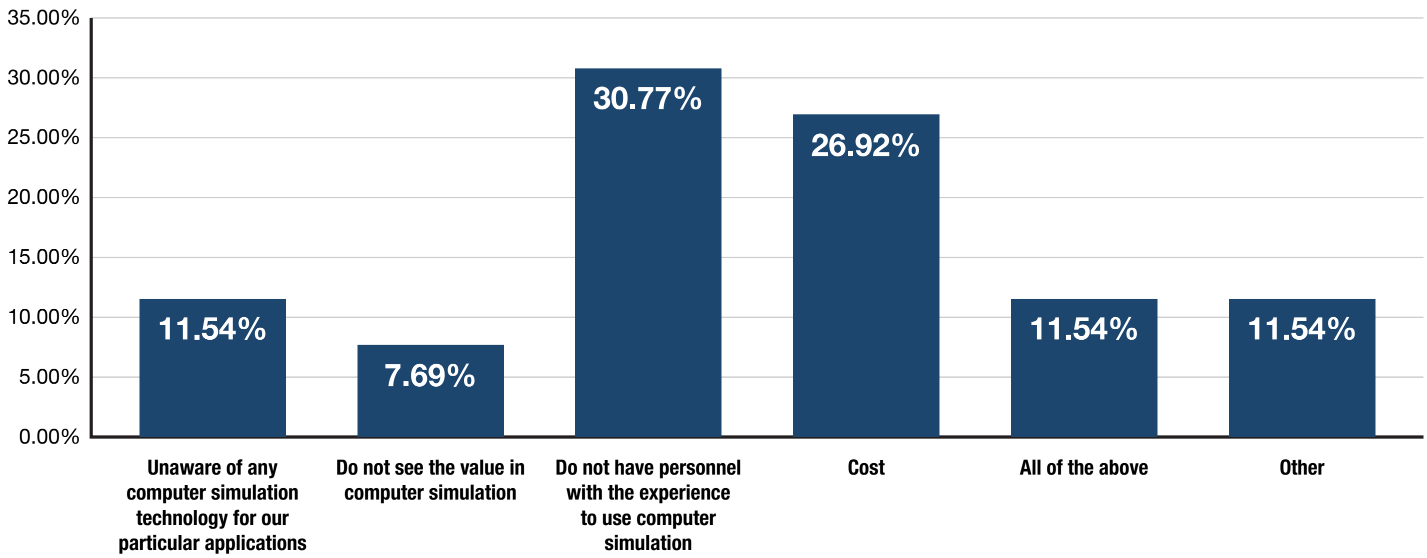
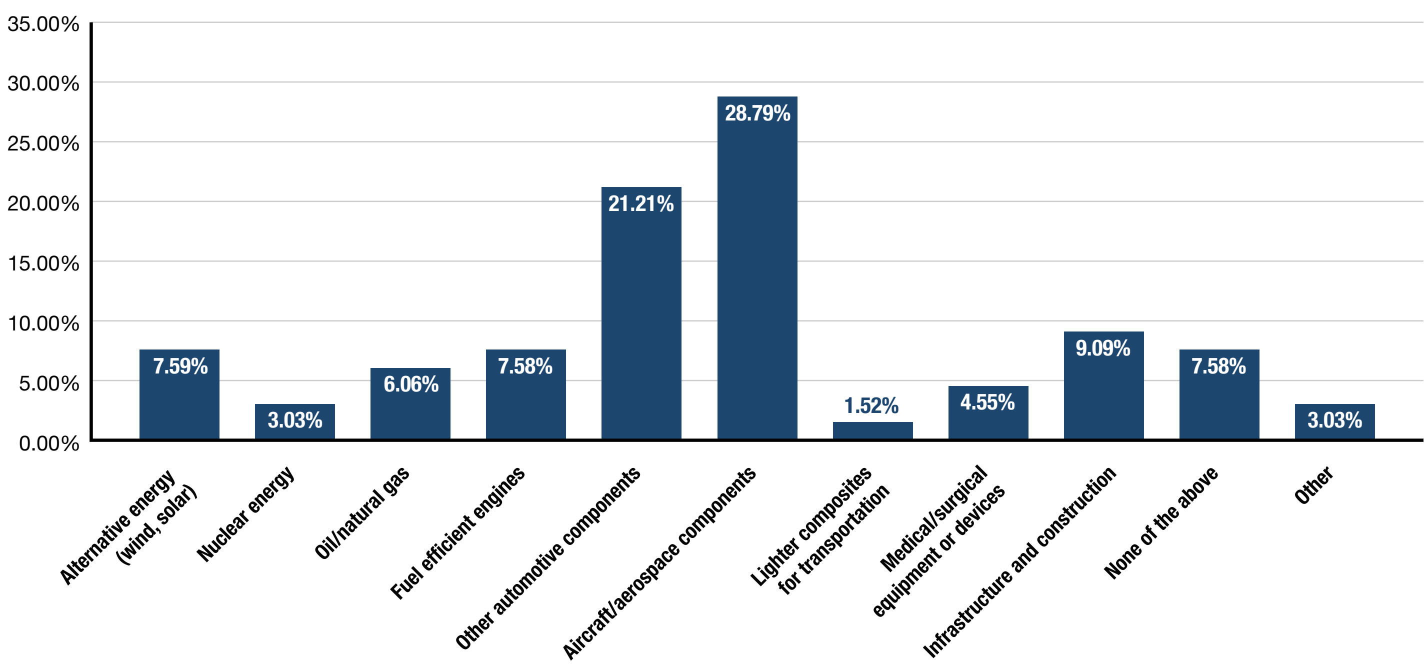


FIGURE 2.2: WHICH OF THESE MARKET AREAS OFFERS THE MOST PROMISE FOR YOUR FORGING COMPANY?[189]



Unit Cost

Because hypersonics supply chains are still fairly nascent, the cost per unit – particularly for early prototypes and low-rate production systems – has been relatively high, though estimates are all preliminary and include different assumptions. Since specialty materials are not widely available, nor produced at scale, this drives the cost up overall. A constant message heard from senior DoD and Congressional leadership is the need to reduce the cost per unit for hypersonic systems. As Under Secretary of Defense for Research and Engineering Heidi Shyu explained, "We need to figure out how to drive towards more affordable hypersonics. And that's a piece I would like to help industry focus on: how can we develop affordable hypersonics materials and manufacturing processes to drive the cost down?"[190]

It is important to note that system affordability is not quantifiable per se, since it depends on a complex set of prioritization decisions within the Pentagon, White House, Congress, and industry. However, there are several different factors, regarding the capability of hypersonic systems, that can and should be taken into consideration. First, for hypersonic cruise missiles, a comparison could be made to the cost of conventional cruise missiles which typically cost approximately $1M per unit.[191] However, a hypersonic cruise missile brings far more *capability* than a conventional cruise missile; namely, speed and maneuverability, which makes defending against the missiles far more challenging. This increased capability will likely increase development, production, and sustainment costs. It is estimated that air-breathing systems – based on DARPA's HAWC program – will cost approximately $2M per missile.[192] This is a significant drop from the current cost of "tens of millions per unit" currently associated with hypersonic cruise missiles.[193] On the other hand, the Navy's CPS program and the Army's LHRW provide a very different capability and thus are estimated to cost $50M.[194] These estimates are all very preliminary, include different assumptions, are based on limited data and analysis, and are sometimes biased by industry and service parochialism. It is important to note that some reduction in cost will occur through economies of scale as the Department purchases a larger number of hypersonic systems. However, in order to bring the cost in line with the above estimates in the future, significant changes will have to occur in the hypersonics manufacturing base overall.

Long Lead Times

Due to the lack of demand for large quantities of hypersonic weapons and a low supply of components, lead times have grown exponentially. This issue was raised by multiple working group participants regarding several different components. The current long lead times, in turn, prevent the hypersonic industry from moving quickly. Because the U.S. is still in the prototype phase of fielding hypersonic systems, there is little economic incentive for multiple hypersonic component suppliers to enter the market and, therefore, reduce lead time. Overall, the longer lead time does not only apply only to hypersonics, but across the defense manufacturing ecosystem. Competition for components goes beyond military applications, as the defense industry must compete for resources with non-defense commercial companies, creating strains on the supply chains of products and components even where DoD is the sole customer. As discussed elsewhere in the report, this is especially true for components that overlap with commercial aerospace and space applications. Given the tremendous recent growth in the space industry, this competition for components and resources will likely continue. However, in the long-term, this overlap could benefit hypersonics by growing the supply base to meet increasing demand.

Data Sharing & Storage

Within the hypersonic manufacturing base, the current data sharing infrastructure is cumbersome, crossing different entities with varying protocols. This is particularly problematic for controlled unclassified information (CUI) and classified data. As multiple working group participants noted, government compartmentalization makes sharing information difficult, resulting in an environment riddled with redundant and inefficient processes. Even at the unclassified level within the private sector, companies differ in how they share proprietary data. This leads to confusion at lower-level suppliers over different databases as it is largely the original equipment manufacturers (OEMs) who have internally invested in developing processes. This, in turn, creates redundancy between companies with no way to share information at a common level. Until a more efficient and secure protocol for sharing information can be implemented, the hypersonics manufacturing base may continue to move slowly relative to growing demand.

Testing Infrastructure

Testing infrastructure, while not traditionally considered as a component of supply chains, plays a crucial role in moving hypersonic systems from the early developmental phase to a fully fielded system.[5] Therefore, it was deemed within the purview of this study. A constant theme throughout the working groups was the insufficiency of current national hypersonics testing infrastructure. While a full, detailed analysis of testing infrastructure could be the subject of an entire study, and has been on several occasions, this report will only touch on a few key issues.[6]

There are two broad categories of test facilities needed for the maturation of hypersonic technologies – ground and flight. The first category includes hypersonic wind tunnels (HWTs), that are generally less expensive to operate and allow for easier collection of data compared to actual flight. HWTs simulate air flow and ultra-high temperatures that hypersonic vehicles need to withstand in-flight. The second category is an open-air range, which enables actual flight of a hypersonic prototype or testbed. Open-air ranges provide

5 A list of testing infrastructure can be found in Annex A

6 For examples, see "Advanced Hypersonics Test Facilities" edited by Frank Lu and Dan Marren or "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"

the space for putting a hypersonic missile on the vehicle's surface itself, enabling testers to better mimic the conditions of the atmosphere. Both facilities simulate the unique conditions experienced in hypersonic flight (e.g., speed, pressure, and heating) and are instrumental for hypersonic development.

Among the biggest constraints to the development of hypersonic technology is the inadequate testing infrastructure in the U.S. According to a study conducted by the Institute for Defense Analyses (IDA), the U.S. had only 48 specialized hypersonic test facilities and mobile assets in 2014.[195] The facilities are a mix of government, academic, and business entities, including: 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."[196] While this study was completed almost 10 years ago, only a few minor changes have occurred since. Two encouraging developments (that will be discussed in more detail below) are that a few universities have begun building additional testing facilities and DoD has very slowly begun to explore limited changes to increase testing infrastructure. It is challenging to quantify exactly how many more facilities are needed. However, additional capacity is required for several different reasons raised by working group participants.

First, hypersonic systems must compete for test time slots with current high-priority programs, such as missile defense and nuclear deterrence. While DoD leadership has emphasized the importance of hypersonic systems, these other programs have been prioritized in scheduling tests. This is partly due to a lack of a hypersonics program of record and due to the other programs being prioritized by the DoD. The ensuing limited range access for hypersonic flight testing creates inefficiencies. As hypersonic tests are pushed from the schedule to make room for established programs of record, this causes cascading delays to technological development as programs wait months to reschedule.[197]

Consistent access to these facilities for ground testing is particularly vital to determine which materials are needed for hypersonic development. One workshop participant noted that optical window materials, for example, have been an ongoing concern for industry, in part because of limited testing capacity. Experiments testing optical window materials in hypersonic flow are necessary to address challenges related to efficient cooling at high speeds and the ensuing high temperatures.[198] Studies dating back to the 1980s and current SBIR/STTR contracts attempt to provide solutions to address this challenge.[199] However, the longevity of the issue reflects the poor quality of testing, which hinders industry's ability to collect the appropriate amount of data to adequately pull meaningful results.

A second issue is the age of existing testing infrastructure. Most testing facilities were built decades ago and personnel at the facilities are not accustomed to working at the tempo that is now necessary to keep up with all programs. With this high operational tempo, fatigue sets in and machines break. When one machine goes offline, there is not enough redundancy built in and testing is temporarily halted. Older testing infrastructure also lacks efficient data acquisition. If data acquisition was modernized at testing facilities, this could reduce the number of tests necessary since each test could yield significantly more data.

Current modes of testing also tend to be extremely expensive and difficult to coordinate. For example, the Navy's CPS system has required a "string of pearls" of ship-borne assets across the ocean in order to collect data.[200] However, the Test Resource Management Center (TRMC) is attempting to address this through the SkyRange program, which uses twenty RQ-4B Global Hawks as hypersonic test support.[201] The goal of the SkyRange program is to increase hypersonic testing, meeting the Department's test cadence of "50-plus tests a year."[202] TRMC and the Office of the Principal Director for Hypersonics are also working with the Space Development Agency, Space Force, and Army to study how satellites could be used to support hypersonic testing.[203] TRMC is also leading the development of the Multi-Service Advanced Capability Hypersonics Test Bed (MACH-TB) program, which aims to validate and field hypersonic systems at a higher frequency through a new testing facility.[204] Each of these programs are a step in the right direction but only time will tell if they are successful.

Finally, even once the current first-generation hypersonic systems have reached sustainment, modernized, expanded testing facilities will still be needed for the future. A higher tempo of regular S&T flight testing will be necessary to solve key S&T or physics questions for future generation hypersonic systems. Furthermore, as systems are continuously updated with more modern software, materials, and microelectronics, significant continuous testing of the system and subsystems will be required.

Overall, the current U.S. testing infrastructure is insufficient to meet the demands laid out by the Defense Department itself for hypersonic development over the coming years. Even if the rest of the hypersonics manufacturing base were scaled up, aging testing infrastructure would significantly hinder production. Therefore, modernizing and expanding testing infrastructure to support hypersonic programs is a necessary link of a secure, resilient supply chain.

WORKFORCE

Lack of Hypersonic Talent

The hypersonics industry – defined by a workforce lacking substantial experience working on large-scale hypersonic projects – faces an uphill battle in developing a stable supply of hypersonic professionals due to the volatile history of the technology's development. Unfortunately, it is difficult to estimate exactly how large the existing hypersonics workforce is in order to then determine what type of growth is necessary over the coming years. However, a few conclusions can be drawn from the insights of the working groups, subsequent interviews with experts in the field, and internal research. At the same time, trends from the larger aerospace industry workforce likely impact the hypersonics workforce as well and should be considered. As such, this section will summarize the key insights and concerns from the working groups, interviews with experts, and internal research in the larger context of the aerospace industry workforce, and attempt to provide actionable recommendations to address them.

Overall, the aerospace industry faces many of the same issues facing other sectors in the post-Covid era.[205] The industry has seen rising employee turnover with 69% of respondents to a 2022 Aerospace Industries Association survey stating that turnover increased in the last 12 months.[206] At the same time, there are reports of an industry-wide shortage of talent, especially for workers with engineering skills and strong digital capabilities, despite increasing demand due to the rebound of air travel from the pandemic, the need for advanced defense capabilities due to rising geopolitical tensions, and a renewed vision and prioritization of space travel and deep space exploration.[207] The hypersonics workforce, as a subset of the larger aerospace industry workforce, likely faces similar challenges that are compounded by additional concerns raised by the working groups. According to one working group participant, the current hypersonic-specific expertise is unbalanced and misaligned to current needs. There is a plethora of early and mid-career aerothermal expertise, but a dearth of expertise in other needed areas such as hypersonic controls, system design, and high temperature materials. At the same time, the current hypersonics workforce lacks experience working on large-scale prototypes and system integration challenges as systems scale up from R&D to production.

The hypersonic workforce can be divided into five general groups, along the lines of five different aspects of the technology:[208]

1. **Hypersonic-specific technology experts.** Certain requisite expertise is applicable only to hypersonic vehicles and their flight regime. Development of the necessary knowledge and expertise in these technology areas requires specific study and experience accrued over a period of years.
2. **Workforce that can adapt existing technologies to the specific applications of hypersonics.** Other technologies used in vehicle design must be adapted to the severe hypersonic environment. It is likely that technologies from other flight regimes can be adapted to the hypersonic environment. Under some circumstances this can be better and more cost-effective than creating new and unique disciplines.
3. **Workforce that combines structures, aerodynamics, engines, communications, sensors, controls, etc., into an integrated operational system.** The lack of personnel experienced in vehicle integration and overall hypersonics systems engineering is perhaps the most important issue facing the hypersonic workforce today.
4. **Project management for hypersonic vehicle development.** The integrated design, building, and testing of a hypersonic vehicle requires project managers with unique expertise. This expertise is largely due to special aspects of components used in the hypersonic environment and the blending and integration of those components into a vehicle.
5. **Craftsmen and supporting staff, including machinists, technicians, and other skilled experts.** The craftsmen include individuals responsible for activities like installing wind tunnel models, installing instrumentation, precision machining, and systems and infrastructure maintenance and repair. On the supporting side are those who are not subject matter experts, but instead can support engineering activities and rationalize the overarching policy, management, market dynamics, and other business factors that will shape and control program activities.

According to the working groups and interviews with experts, each of these hypersonics workforce sectors faces its own challenges and issues. First, the workforce overall is dominated by late-career professionals and thus a portion is close to retirement. Among the aerospace and defense talent, 28% of the workforce is aged 55 and older, and 42% of the overall workforce has less than five years of tenure at their current company.[209] The working group participants described a similar hypersonics workforce. This is likely due to a heavy emphasis by the U.S. government on hypersonic systems several decades ago. This emphasis led to an increased number of professionals entering the hypersonics workforce. However, that emphasis has ebbed and flowed over the years, and with the uncertainty, fewer professionals have entered the workforce.

Another important insight from the working groups pertained to the level of education necessary to work in hypersonics. While certain jobs may require a doctoral level of education, for much of the hypersonic workforce a bachelor's, master's, or even a high school diploma is sufficient. In addition to an aging hypersonics workforce and the necessity for professionals with varying levels of education, several other factors were highlighted by the working groups and experts as impacting the workforce.

Clearance Process Stymies Development of Needed Workforce

Though not specific to hypersonics, the clearance process keeps the industry from moving quickly. Participants in the working groups highlighted that this issue affects nearly all sectors of the workforce and at all levels. One particular issue raised in the working groups is the challenge of clearing students so they can work on relevant research while still in school and be ready to join the workforce immediately upon graduation. Similar issues plague mid-and-senior level talent as well. With clearance processing timelines of 12-18 months, valuable time is wasted.[210] This is an issue that goes far beyond hypersonics, but if hypersonic systems are truly a priority for the DoD and there is a need to move quickly, this talent supply chain issue must be addressed.

Increased Strain on Testing Facility Personnel

As discussed above, many of the testing facilities used for hypersonic purposes are shared with nuclear modernization efforts. As such, with the increased testing in current nuclear modernization efforts and the existing hypersonic tests, the personnel at these facilities are facing a much higher tempo of tests than they are accustomed to. The increased workload leads to fatigue and burnout, which can result in mistakes, broken machines from the heavier strain and as such, limited systems going offline for repair; further increasing lead-times for hypersonic tests. The silver lining to the increased testing, however, is a more experienced testing facility workforce as additional test shifts are added to keep up with increased demand.

SUMMARY

Both the current hypersonics manufacturing base and the hypersonics workforce are insufficient to support hypersonics production in the future. While multiple issues plague both sectors, a lack of consistent demand signal from the Department of Defense has exacerbated the problem. Without a guaranteed return on investment, companies will not invest time, money, and resources into scaling up production. At the same time, individuals may not enter the hypersonics workforce if the viability of programs, and therefore positions, is in question. The first step in scaling up the hypersonics industrial base must be a consistent demand signal from the government. Several other steps must also be taken in order to secure hypersonics supply chains for the future.

RECOMMENDATIONS

1. The Department of Defense should provide a consistent and clear demand signal to industry by treating certain hypersonic programs as traditional Programs of Record and utilizing multi-year contracts to send an extended demand signal.

The most important, immediate step that the Department of Defense can take to strengthen hypersonics supply chains of the future is to send a consistent demand signal to industry. All of the working groups raised this as a significant barrier to scaling up the hypersonics industrial base. The clearest way to send this demand signal is to treat certain hypersonic programs as programs of record (POR), by including funding in the Department of Defense annual budget request to move them to production and deployment. Similarly, the Department should utilize multi-year contracts for hypersonics in order to not only send a clear demand signal but one that also extends into the future. While a number of hypersonic programs show promise, HACM is likely the furthest along in development and therefore ready for POR designation.

2. Office of the Under Secretary of Defense for Acquisition and Sustainment (OUSD (A&S)) needs to ensure the acquisition workforce is adequately prepared for hypersonics through education and training.

The traditional acquisition workforce will play a bigger role in hypersonics as programs transition from science and technology and prototyping, into formal Programs of Record. According to one of the working group participants, the acquisition workforce is unprepared and lacks the expertise necessary for hypersonics. OUSD (A&S) leadership needs to prioritize preparing the acquisition workforce through necessary education and training.

3. Additional testing infrastructure should be funded jointly by DoD and industry at appropriate academic institutions in order to help replace aging testing infrastructure.

During the working groups, several participants highlighted the benefits of building wind tunnels and other testing infrastructure at academic institutions. According to several participants, the most pressing need is for additional arc jet facilities providing ground-based hyperthermal environments in support of activities in thermal protection materials and vehicle structures.[211] Building additional testing facilities, including an arc jet, at academic institutions has a number of benefits. First, this location allows students to get "hands on" hypersonics experience prior to graduation. Second, when the facilities are not being used for testing on current hypersonics programs, they can be used for researching and testing future generation hypersonics systems. Finally, students could be placed under contract or in other arrangements so that they have the opportunity to receive clearances prior to graduation, expediting their time to join the hypersonics workforce upon graduation. While not insurmountable, one significant issue of developing these facilities at academic institutions is ensuring their security. Academic institutions are built for open transmission of information and often have large populations of non-U.S. citizens. Given the sensitivity of some hypersonics research, it is imperative that rigorous security measures be implemented at testing facilities. Currently, new testing infrastructure is being built at various universities around the country. This is a step in the right direction, but this should be replicated at other universities across the country in order to support hypersonics supply chains going forward. DoD and industry should engage with applicable universities to both gauge interest in the development of new testing infrastructure, and to discuss the benefits and potential next steps.

Purdue University

Over the past 20+ years, Purdue University has constructed a variety of hypersonics testing infrastructure. In the early 2000s, Purdue engineers built a Mach 6 quiet wind tunnel funded by the Air Force Office of Scientific Research, the Ballistic Missile Defense Organization, and the Boeing Company, among others.[212] Twenty years later, in summer 2021, Purdue announced construction of two new facilities. The first, the Hypersonics and Applied Research Facility, would house a Mach 8 quiet wind tunnel as well as a hypersonic pulse (HYPULSE) shock tunnel. The second facility, the Hypersonic Ground Test Center (HGTC), included two separate testing streams; one where partners could conduct tests in the Mach 3.5-5.0 range and the other in the Mach 4.5-7.5 range.[213]

Texas A&M University

Over the last 20 years, Texas A&M University has constructed a suite of hypersonics test facilities funded by the Air Force, Army, NASA, Navy, State of Texas, and the Texas A&M System. These include the NASA Langley Mach 6 Quiet Tunnel (M6QT), a large scale (3.0-ft exit diameter) hypervelocity expansion tunnel (HXT), which operates between Mach 4 and 25, and a variable Mach 5 – 8 Actively Controlled Expansion tunnel (ACE)[214] In addition, Texas A&M is constructing a large-scale enclosed Ballistic, Aero-Optic, and Materials (BAM) range to provide ground-based access to flight conditions up to Mach 15.[215]

4. The defense industry should ensure that it has the traditional and additive manufacturing capabilities needed to produce hypersonics at scale.

It is clear that improvements in traditional and additive manufacturing play a role in the cost reduction and overall performance of hypersonics. Boosting domestic manufacturing will require embracing automation in factories. One working group participant reiterated this point, arguing automation can help with single source issues.[216] Both industry and DoD have shown interest in available additive manufacturing capabilities and continue to pursue research exploring new applications. As the number of hypersonics procured by DoD increases, the defense industry will need to verify it has the internal additive manufacturing capabilities to meet demand. Conversely, DoD will need to demonstrate that industry investment in additive manufacturing capabilities will ultimately be worth the financial cost. DoD should publicly state its plan to pursue contracts that utilize additive manufacturing and other advanced manufacturing processes. This will demonstrate an additive manufacturing and automation demand signal that will give investors clear insight into the DoD's plans for the future.

5. The Cost Assessment and Program Evaluation Office (CAPE) should develop realistic independent life cycle cost estimates for current planned hypersonic weapon systems that factor in inventory goals, development, production and technology refresh and sustainment costs.

These estimates can then be used to inform debates on prioritization of different approaches to developing long range fire capabilities and to help decision-makers prioritize between hypersonic weapons programs. Currently, there is little consensus regarding unit costs for both boost-glide and air-breathing systems. In order for policymakers to make informed decisions, there needs to be a central source that provides cost estimates that consider the hypersonic program inventory goals and development and production costs.

6. DoD and Congress should continue to adequately fund S&T for future generation hypersonic systems.

While current hypersonic systems must be funded and fielded quickly, Congress should continue to look towards the future and adequately fund S&T research for future generation hypersonic systems. Existing hypersonics programs certainly need to be adequately funded but funding S&T is vital for securing hypersonics supply chains in the future. This funding sends an early signal to industry so the appropriate manufacturing base and workforce will exist when needed. It also provides for the fusion of between new capabilities and existing programs, enabling industry to keep their most technical hypersonic design engineers current in latest technological advancements. With adversaries already focused on next-generation hypersonic systems, the Pentagon should continue to request sufficient funds and Congress should continue to support requested S&T for future hypersonic systems in order to strengthen future supply chains.

7. OUSD R&E should continue to pursue an air-breathing hypersonic vehicle system as a key element of its development plan.

The only means to maintain existing expertise and to develop new expertise in hypersonic vehicle technologies is through a development program with a sustained funding level sufficient to meet the Department's needs. An airbreathing hypersonic vehicle system development program will facilitate the transfer of crucial expertise from seasoned experts to new entrants into the field. Special aspects of hypersonic vehicle design can be transferred via apprentice training —the craft and guild model. An important consideration is the development of personnel with expertise in hypersonic systems integration. This expertise has never been fully developed, given that an airbreathing hypersonic vehicle has never been realized. The expertise obtained in past programs is an important source of lessons learned, but these lessons were frequently undocumented. A coherent, focused, and fully documented development program is the optimal mechanism for retaining core personnel and ensuring the transfer of costly lessons learned to the next generation.

8. Congress should direct DoD to maintain a continuously updated assessment of the testing infrastructure needed to support current hypersonic research and development and production activities.

The Test Resource Management Center (TRMC) looks across the entire Test & Evaluation (T&E) infrastructure to align T&E efforts with DoD modernization goals. TRMC ensures the DoD T&E community has the right set of capabilities to meet the current and future needs of the warfighter. Congress should not fund programs that have insufficient test infrastructure planned or in place to support stated goals for development and production. As such, regular T&E assessments by TRMC will help mitigate wasteful spending and support hypersonic development and production.

9. The U.S. Intelligence Community (IC) should include a regular assessment of Russian and Chinese defense emerging technology supply chains, including hypersonics, in their ongoing assessments.

Given the apparent progress of Chinese and Russian hypersonic programs, the IC should include regular assessments of Chinese and Russian defense emerging technology supply chains including hypersonics supply chains in their analysis of these efforts. These assessments should include all tiers of their supply chains, to include workforce and testing infrastructure. This will not only serve to inform policymakers but also help identify actions the U.S. can take to slow the progress of adversary programs, and identify ways in which the U.S. can prevent domestic assets from unwittingly supporting adversarial efforts. Where possible, the IC should disseminate findings to relevant industry stakeholders to facilitate both awareness and cooperation regarding these efforts.

10. DoD should increase the hypersonics flight test schedule.

The existing hypersonics test frequency, often a dozen flights a year or less, is inadequate to effectively move production forward.[217] To bring down costs, gather more data on the different hypersonic programs, and solve key current and future S&T and physics questions, the number of tests for both air-breathing and boost-glide hypersonic systems should be greatly increased. Some experts believe testing should occur on a weekly basis.[218] Ideally, these tests should focus on highly specific areas of the systems instead of traditional, all-encompassing evaluations. Limiting the number of simultaneously tested variables reduces the complexity of the overall experiment and should contribute to rapid progress. Emphasizing the need for recoverable components would further contribute to the rapid testing process.[219] Additionally, commercial partners should be harnessed to cut costs and increase the frequency of test flights.[220] Ultimately, regular tests are critical to the advancement of the U.S. hypersonics technology and affordable fielding of the systems.

11. The Department of Defense should continue to encourage the use of digital engineering techniques and technologies in its hypersonics programs in order to reduce costs, allow for rapid system upgrades, and streamline maintenance.

Digital engineering, defined as "the integration of data provided across industry and government engineering disciplines through the use of commercially and DoD-developed tools to support lifecycle activities from concept development through disposal" is a powerful tool, identified by the working groups, to strengthen hypersonics supply chains.[221] Creating digital models of the entire hypersonic system allows engineers to increase and improve testing before building physical prototypes and increases the speed of finding interferences. Expanded digital testing provides substantial opportunities for cost reduction and rapid advancement. Some defense companies have already mandated the use of digital engineering. Considering this tool's potential, the DoD should continue to pursue, and publicly reaffirm its commitment to, contracts and programs that incorporate digital engineering to reduce research and production costs, streamline maintenance, and facilitate rapid system upgrades.

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12. DoD should encourage venture capital to invest in areas where the hypersonics supply chains and growth of the space industry overlap.

Venture capital typically looks for investment areas after the basic and applied research stage and only invest when there is an anticipated large payoff. Many working group participants described the apprehension amongst venture capital investors due to the absence of hypersonic programs of record. Therefore, it is recommended that venture capital funding should go where the needs of the hypersonics supply chains overlap with the dramatic growth of the space industry. These areas could include propulsion, high temperature materials and other advanced materials, additive manufacturing, modeling and simulation, and system recoverability. To encourage investment, it is DoD's responsibility to ensure clear and consistent communication with industry leaders so that the Department's desired end state for hypersonics is well understood by industry. As such, it is important for DoD to reassure industry that investment in hypersonics will be met with programs of record.

13. DoD should request additional funding for the University Consortium for Applied Hypersonics (UCAH) to focus on hypersonic leap-ahead technologies.

Since the UCAH was established in 2020, the number of university and industry participants has increased significantly. At the same time, current DoD leadership identified hypersonic leap-ahead technologies as a high priority in the *2022 USD(R&E) Technology Vision for an Era of Competition*.[222] The growth of the UCAH provides a tremendous opportunity for DoD to leverage the tremendous expertise of this group to focus on important, high priority topics. Thus, DoD should request additional funding for the UCAH to focus on leap-ahead technologies, as prioritized by current OUSD R&E leadership.

WORKFORCE RECOMMENDATIONS

1. Academia should be leveraged, via the University University Consortium for Applied Hypersonics (UCAH), to educate mid-level hypersonic talent.

Within the academic community, there is a wealth of knowledge on hypersonics that should be leveraged to provide workforce training to mid-level talent in hypersonic-adjacent fields. Some work has already been done in this area. Several large companies have brought senior faculty from the UCAH to train their technical staff on hypersonics and UCAH leadership is working to create recorded short courses to expand this opportunity. This is a step in the right direction, but it must be scaled up considerably to address the dearth of mid-level hypersonic talent. The UCAH should build on its current work to increase the size and scope of the courses, at appropriate classification levels and with appropriate controls in place, to reach a wider audience.

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2. DoD should continue to leverage the Science, Mathematics, and Research Transformation (SMART) Scholarship Program to help strengthen and retain the early career hypersonics workforce.

DoD's Science, Mathematics, and Research Transformation, or SMART, Scholarship is a highly competitive program to enhance the DoD civilian workforce with innovative scientists, engineers, and researchers.[223] In exchange for tuition assistance and other benefits, students enter public service upon graduation for a set period. While this program is rightly focused on areas beyond hypersonics, it is a valuable way to help strengthen and retain early career hypersonic talent. Recent reports indicate that the Defense Department is considering expanding the program to do just that.[224] This is an important step in the right direction and should be quickly implemented to increase the early career hypersonic workforce.[225]

3. OUSD R&E should use existing faculty fellowship programs, including the Vannevar Bush Fellowship and the Defense Science Study Group, to incentivize stellar faculty with expertise in hypersonics-adjacent fields, who are not currently working in national defense, to focus their research on next generation hypersonic systems.

The Vannevar Bush Fellowship is DoD's most prestigious single-investigator award supporting basic research with the potential for transformative impact.[226] While the fellowship is intended for faculty not currently working in national defense, it frequently is awarded to those already working in this space. This misses a tremendous opportunity to incentivize stellar faculty to enter the national defense basic research arena. DoD leadership should refocus the program on its original goal by looking to faculty working in areas that could have significant impact on national security but are not currently involved. While the fellowship does – and should – focus on a variety of research topics, DoD leadership should look for proposals in hypersonic or hypersonic-adjacent fields that could contribute to making the jump to next generation hypersonics systems. Similarly, the DSSG (directed by the Institute for Defense Analyses but sponsored by DARPA), introduces a prestigious group of faculty to key national defense issues over the course of a two-year program through site visits, meetings with senior defense leadership, and discussions.[227] Again, while the fellowship should continue to cover areas outside of hypersonics and emerging technologies, DoD would be remiss if it did not use the fellowship as an opportunity to encourage faculty to focus their research on key hypersonics issues of the future. While not losing focus of the immediate need to field hypersonic systems at scale, DoD should use existing tools to focus research on the issues of the future and next generation hypersonic capabilities.

4. DoD should conduct a study of the existing hypersonics workforce and share the results with industry to identify and address concrete shortfalls in order to scale up hypersonic production.

The lack of publicly available data on the existing hypersonic workforce presents a challenge for assessing this dimension of hypersonics supply chains. Comments from experts and professionals closest to the work, however, are insightful. To truly address the suspected shortfalls, DoD should conduct a study, and share the results with industry in order to focus efforts in the most cost-effective and impactful manner. The study should not only include data regarding the status of the hypersonic workforce, but also recommendations on how industry and government can work together to address current and anticipated shortfalls. The study could identify which government and academic programs or policies the hypersonic workforce is or is not utilizing. The study can then serve as a foundation for clear and consistent communication going forward.

CHAPTER 3: SUPPLY CHAIN SECURITY & VULNERABILITIES

KEY ISSUES:

- Cybersecurity Risks
- Counterintelligence & Economic Espionage Risks
- Intellectual Property Theft

ASSESSMENT OF THE SECTOR

Hypersonics supply chains, like other emerging technology supply chains, face a range of threats related to cybersecurity, counterintelligence, and intellectual property theft. While hypersonic-specific examples can be challenging to find in open-source information, some significant conclusions can be drawn from an analysis of recent and historical examples from related industries, in addition to issues raised by the working group participants.

CYBERSECURITY RISKS

Cybersecurity threats to hypersonics supply chains begin at the very lowest tier: mining and production of critical raw materials. As mining operations become more automated, the attack surface area increases.[228] Over the years, mining operations have been subject to attacks from numerous fronts, including nation-state actors, with the same techniques used in other sectors such as phishing, vulnerability exploitation, watering hole attacks,[7] and infected equipment.[229] The goals of such attacks can range widely from commercial espionage to information operations. For example, from 2006 to 2014, aluminum maker Alcoa Inc and metal supplier Allegheny Technologies Inc (ATI) were subject to attacks allegedly originating from the Chinese People's Liberation Army (PLA).[230] While exact details are unclear, the hack seemed focused on gaining internal messages related to a February 2008 partnership with a Chinese state-owned company to acquire a substantial stake in a foreign mining company.[231] ATI also entered a joint venture with a Chinese state-owned company in 2012.[232] During the attack, the hackers allegedly gained access to network credentials for virtually every employee at a company with approximately 9,500 full-time employees in the aerospace, defense and "specialty materials solutions" sectors.[233]

More recently, an American cybersecurity firm reported on efforts by the People's Republic of China (PRC) related to a "subset of information operations activity…across social media that targeted the Australian rare earths mining company, Lynas Rare Earths Ltd."[234] The activity was one small part of a larger influence campaign, called DRAGONBRIDGE, intended to promote "various narratives in support of the political interests of the PRC."[235] Not long after, additional attacks took place against the Canadian rare earths miner, Appia, and the American rare earths supplier, USA Rare Earths, in response to reports that Appia had discovered "a new rare earths bearing zone in Northern Saskatchewan" and USA Rare Earths announcing "plans for a rare earths processing facility…"[236] It is likely that the Chinese Communist Party (CCP) saw these commercial entities challenging their dominance in rare earth mining and processing as a threat and thus attempted to undermine the credibility of those commercial entities.[237]

Moving up through the supply chain, hypersonic system manufacturers may face similar cyber threats. According to reporting by the Cybersecurity and Infrastructure Security Agency (CISA), Russian state-sponsored cyber actors have targeted small and large U.S. cleared defense contractors (CDCs) and subcontractors "with varying levels of cybersecurity protocols and resources."[238] While the exact companies are not named, CISA reports that the CDCs are supporting contracts for the DoD on "command, control, communications, and combat systems…weapons and missile development; vehicle aircraft design; and software development, data analytics, computers, and logistics."[239] Given the breadth of systems targeted, and the fact that Russia has had a robust hypersonics program over the years, it is possible that CDCs working on hypersonics systems are among those targeted.

During the working groups, industry members raised several similar cybersecurity concerns that they, or their suppliers, face on a regular basis.[240] First, the smaller, low-tier suppliers lack the necessary resources for robust cybersecurity measures. The business case is almost non-existent for these small companies to invest in the necessary infrastructure for cybersecurity measures unless they can make a profit in five years – a challenge when the customer is the DoD. Another cyber vulnerability raised by working group participants was the issue of software supply chain attacks. A few suppliers use foreign-made software, which may leave them vulnerable to attacks. According to the CSIS Significant Incident Reports, numerous Chinese hackers have also engaged in cyberattacks against U.S. aerospace companies over the years, including using a malware known as "Sykipot" to target U.S. defense aerospace companies.[241]

Universities and National Labs conducting hypersonics research and testing have also faced cyberattacks over the years. In 2018, the Australian National University (ANU), which conducts hypersonics research, was allegedly breached by Chinese hackers.[242] Exact

7 In a watering hole attack, the attacker compromises a site likely to be visited by a particular target group, rather than attacking the target group directly. https://csrc.nist.gov/glossary/term/watering_hole_attack

details are unclear, but according to Australian Strategic Policy Institute's executive director Peter Jennings, the goal of the attack was to access and extract intellectual property from the institution.[243] Oak Ridge National Lab, which has conducted significant research pertaining to modeling the flow of objects in hypersonic flights as well as research aimed at understanding combustion at hypersonic speeds, was subject to a sophisticated cyberattack in 2011.[244] Although full details on the attack are unclear, the lab was forced to shut down its e-mail systems and internet access for all employees when they discovered they were a victim of an advanced persistent threat to steal technical data.[245] Again, it is unclear if these attacks directly targeted hypersonics research and data, but these examples still show significant cyber vulnerabilities within organizations at various levels of hypersonics supply chains.

COUNTERINTELLIGENCE & ECONOMIC ESPIONAGE RISKS

While many current counterintelligence threats to hypersonics supply chains may be classified or not available in the public domain, it is possible to evaluate potential threats based on the reported actions of adversaries and similar historical examples.

China's technology transfer efforts have become well-known over the past several years. President Xi Jinping has emphasized that in order for China to "grow strong, prosperous and rejuvenated,"[246] it must "become the world's main center of science and the high ground of innovation."[247] Hypersonics is just one example where China has used both legal and illegal means to field a technology before the U.S.[248] Research and development of hypersonic systems in the United States began as early as the 1960s, while Chinese work did not begin in earnest until the mid-2000s.[249] Given a nearly 40 year difference, how is it that the U.S. has yet to field a single hypersonic weapon, while China has fielded several and conducted multiple tests on others? While the answer is long and complicated, one factor that potentially accelerated the Chinese programs was the legal, or illegal, acquisition of U.S. research and technology. To be sure, the United States failed to maintain the momentum of its hypersonic programs over the years. If the momentum had been maintained and a clear, consistent focus on fielding hypersonic systems had continued, the U.S. not only would have outpaced China but many of the existing hypersonics supply chains issues would perhaps not exist. Unfortunately, the reality is that early on, China took note of U.S. hypersonic work, including several open policy documents that explained the value of hypersonic weapons.[250] As the U.S. wavered in its commitment to fielding these weapons, China took advantage of the previous work conducted by the U.S. and others, to expedite their hypersonic programs.

According to a recent report on the issue, China also recruited several former scientists from Los Alamos National Lab to work on their hypersonics programs.[251] One example is Chen Shiyi, an expert in fluid dynamics and turbulence, "who has made major contributions to China's hypersonic missile and aerodynamics programs."[252] After working at Los Alamos National Lab from 1990-2000 and serving as the deputy director of the lab's Center for Nonlinear Studies, Chen joined Johns Hopkins University in 2001 to serve as chair of the Department of Mechanical Engineering.[253] In 2005, Chen returned to the PRC to help establish Peking University's engineering college and eventually rose to the role of director of PKU's State Key Laboratory of Turbulence and Complex Systems (LTCS).[254] Allegedly, research that used wind tunnels "built during Chen's time as PKU engineering dean and LTCS director made 'important contributions' that allowed 'the PRC to surpass the U.S. in airbreathing vehicle research and development."[255]

Chinese transfer of expertise for hypersonic programs reaches to the semiconductor level. In 2016, Qualcomm, an American semiconductor company, agreed to a joint venture with Huaxintong, a Chinese company, to develop server chips. While the joint venture was closed in 2019, after producing little of value, some expertise "appears to have transferred to other Chinese companies building… data center chips."[256] Allegedly, at least one chip design engineer left Huaxintong to work for Phytium, "which the U.S. later alleged had helped the Chinese military design advanced weapons systems like hypersonic missiles."[257] These are just a few examples of how China has legally, and illegally, built up its hypersonic programs with U.S. research and development. [258]

INTELLECTUAL PROPERTY THEFT

Another significant vulnerability in hypersonic system supply chains, and all defense supply chains, is intellectual property (IP) theft. Unfortunately, it is difficult to find hypersonic-specific examples of IP theft in open source. However, lessons can be learned by looking at IP theft across the DIB and other related industries. While IP theft can be committed by many different actors, the U.S. Department of Justice has increasingly publicized indictments of Chinese IP theft. In 2014, the FBI indicted five Chinese nationals for stealing trade secrets from American companies.[259] While not a hypersonic-specific example, this was the first time the U.S. ever brought charges against a state actor for this type of hacking.[260] Almost a decade later, it is challenging to accurately quantify the damage inflicted on U.S. companies through Chinese theft, however, a few examples can shed light on the issue. In September 2022, an engineer was sentenced to 8 months in prison for theft of more than 500 files including trade secrets related to networking chips, that he took prior to resigning from his position at Broadcom.[261] Upon his resignation, he began working for a startup company in the PRC that was "seeking to become a leading chip designer focused on the PRC's domestic market for networking chips at the time."[262]

China has also initiated talent programs, including the "Thousand Talents Program" in order to "attract, recruit, and cultivate high-level scientific talent in furtherance of China's scientific development, economic prosperity, and national security."[263] One such example was the case of Xioaqing Zheng. While Xiaoqing Zheng was an employee of General Electric, he stole valuable intellectual property on advances in gas turbine technologies.[264] Fortunately, GE stopped the flow of IP when their insider threat program monitoring received an anomaly alert.[265] However, until the alert, GE was ignorant of the fact that he was associated with the Chinese Thousand Talents Program for years.[266]

In 2020, United Microelectronics Corporation (UMC), a Taiwanese semiconductor foundry pled guilty to criminal trade secret theft.[267] According to the Justice Department, "UMC stole the trade secrets of an American leader in computer memory to enable China to achieve a strategic priority: self-sufficiency in computer memory production without spending its own time or money to earn it."[268] In another case, a Chinese national was sentenced to 24 months in federal prison for "stealing proprietary information worth more than $1 billion from his employer, a U.S. petroleum company."[269]

In 2021, a Chinese Intelligence Officer, Yanjun Xu, was convicted of conspiring to and attempting to commit economic espionage and theft of trade secrets.[270] Xu targeted companies in the U.S. and abroad "that are recognized as leaders in the field of aviation."[271] After identifying experts at those companies, Xu "recruited them to travel to China, often under the guise that they were traveling to give a presentation at a university."[272] Xu even "attempted to steal technology related to GE Aviation's exclusive composite aircraft engine fan...to benefit the Chinese state."[273]

SUMMARY

While hypersonic-specific examples of IP theft, cyberattacks, and CI threats can be difficult to find in open source, several lessons can be learned from similar cases. First, cyberattacks can and do target all levels of the hypersonics supply chains including mining and processing of critical raw materials like REE and aluminum. Similarly, there have been clear examples of the PRC recruiting hypersonics talent from the U.S. to help build their programs. Finally, IP theft by the PRC has affected many companies and technologies that undergird hypersonics. Overall, there are a number of security vulnerabilities within the hypersonics supply chain that should be addressed by the government and industry.

RECOMMENDATIONS

1. DoD should address major cybersecurity risks at the low-to-mid-tier levels of the hypersonics supply chains by creating a "bug bounty" program for small government contractors working on hypersonics.

A common theme throughout the working groups was the challenge that small companies face in having the necessary resources to invest in robust cybersecurity infrastructure. In 2016, the Department of Defense began the "Hack the Pentagon" initiative that expanded in 2021 to include all publicly accessible defense information systems.[274] Through this system, the Defense Digital Service provides a "bug bounty" program in which hackers are paid for finding and reporting vulnerabilities in DoD systems.[275] Given the success of bug bounty programs and the cost constraints faced by small government contractors, DoD should create a bug bounty program to help secure companies at the lowest tiers of the hypersonics supply chains. While traditionally, the Industrial Base Analysis and Sustainment Program (IBAS) has not been used for cybersecurity, the goal of securing the lower levels of the supply chain from security threats is squarely within the IBAS mission of addressing industrial base issues. Thus, creating a bug-bounty program could be an opportunity for IBAS to address a critical supply chain issue.[276]

2. Defense Industry should leverage cloud service providers to establish a common infrastructure allowing for easier information-sharing and protections against growing cyber threats.

As a community, the hypersonic industry needs a common cloud infrastructure – at scale – that enables different stakeholders to securely share proprietary information and IP. Industry representatives in the working groups – from both large and small companies – expressed the need for a better data-sharing strategy across the supply chain tiers. These participants described varying data-sharing protocols between large and small companies, which is not conducive to growing cyber threats. A common infrastructure, which includes classified cloud tools, minimizes confusion by keeping security protocols simple and common. Using the classified part of the cloud gives the community access to information, while also keeping the right protections and compartmentalization for classified information and IP.[8]

3. The FBI should work with industry and academic leadership at all tiers of the hypersonics supply chain to increase awareness of counterintelligence threats.

Department of Defense Directive 5240.06, Counterintelligence Awareness and Reporting (CIAR) and the National Industrial Security Program Operating Manual, Chapter 2, currently mandate annual Counterintelligence Training for industry and DoD personnel.[277] However, as the Defense Security Service has acknowledged, annual training is insufficient to increase the vigilance needed both inside government and throughout the DIB of the enormous CI threat.[278] Within the DIB and other companies working on hypersonics systems, it is up to leadership to take the initiative to educate themselves and their employees on the CI risks they face. Numerous resources are available through the Defense Security Service in order to do this. However, the FBI should also work with industry leadership and academia at all tiers of the hypersonics supply chains to increase awareness of CI threats. Trade associations can be a useful tool in this regard. Organizations such as ETI's parent National Defense Industrial Association can help by hosting seminars to increase CI awareness within the industrial base overall, but especially with those companies involved in hypersonics.

8 Pilot programs such as the Defense Acquisitions Research Collaboration & Innovation Environment (DARCIE), which aims to establish a foundation for digital acquisition innovation through the development of a data science environment, is an example of an effort aimed at creating a shared data platform that protects sensitive information, accelerates decision making, and drives innovation. (https://dev.acqirc.org/news/tools-that-enable-agility-defense-acquisitions-research-collaboration-and-innovation-environment-darcie/)

4. Industry leadership at all tiers of the hypersonics supply chain should increase awareness of intellectual property theft by foreign adversaries. In addition, industry leadership should take steps to identify and secure cyber vulnerabilities, and screen new and current employees.

Intellectual Property theft is a challenging issue that will need to be addressed by industry leadership at all tiers of the hypersonics supply chains. First, industry leaders need to recognize that no company in the hypersonics supply chain is immune to this threat. Given the clear emphasis the CCP has placed on emerging technologies, including hypersonics, and their long history of stealing intellectual property in order to build up their own programs, every level of the U.S. hypersonics supply chains is vulnerable. While industry leaders must first acknowledge the threat, they also need to ensure their employees are aware of the consequences this threat can have on an entire company – jobs and livelihoods are at stake. Next, given that most IP theft occurs through cyber breaches and human sources, steps must be taken to mitigate these vulnerabilities. While strengthening cybersecurity can be a financial challenge for small businesses, the alternative of having intellectual property stolen and the company going out of business is untenable. As discussed above, the U.S. government should take steps to help offset the cost for small businesses. This step can also have a positive impact on limiting the potential for IP theft. Industry leadership should also craft internal policies, as well as enforce existing policies, to screen new and current employees. Connections between employees and the Chinese Thousand Talents program often go unnoticed until theft or attempted theft occurs. This must be addressed at the company-level through rigorous security screening, and enforcement of international travel reporting requirements. Active security personnel must work to thwart foreign theft of intellectual property from all levels of the hypersonics supply chains. If the U.S. is serious about protecting its hypersonic intellectual property in the future, steps must be taken now in order to address this major vulnerability.

5. The U.S. Government should continue to fund existing programs to track intellectual property (IP) theft within defense emerging technology supply chains, including hypersonics. Furthermore, the U.S. government should continue to develop new systems to track the entire range of IP theft affecting the Defense Industrial Base.

One of the challenges of addressing intellectual property theft within the DIB is first quantifying and tracking instances. Despite this challenge, some programs have made promising headway. For example, the Foreign Investment Review office (Office of the Assistant Secretary of Defense (Industrial Base Policy)), is conducting encouraging efforts to uncover instances of investment-based IP theft. The U.S. Government should conduct an efficacy analysis on current IP theft detection programs while continuing to develop systems to track instances of IP theft within defense emerging technology supply chains. The results should then be made accessible to companies within the DIB. This information can help companies take steps to secure their IP and better educate their employees on the risk.

CHAPTER 4: INTERNATIONAL PARTNERSHIPS & ALLIED NEARSHORING

KEY ISSUES:

- Current International Partnerships and Agreements on Hypersonics
- Allied Nearshoring
- Hypersonics Challenges of the Current Export Control Regime
- Classification Challenges

ASSESSMENT OF THE SECTOR

The U.S. places great value on maintaining alliances and partnerships with like-minded nations around the world to safeguard against growing threats. During the ETI-led working groups, participants assessed the challenges to international partnerships, identifying key issues, areas of success, and opportunities for improvements through policy changes. Overall, international partnerships in hypersonics are limited. Given the sensitive nature of hypersonics technology, this is understandable. However, some steps should be taken to strengthen and utilize existing partnerships in order to better secure hypersonics supply chains.

CURRENT INTERNATIONAL PARTNERSHIPS AND AGREEMENTS ON HYPERSONICS

Multilateral Partnerships

The United States currently has two multilateral partnerships in place on various aspects of hypersonics. First, through the AUKUS partnership, Australia, the United Kingdom, and the United States, agreed to increase trilateral collaboration on several defense capabilities and emerging technologies. Hypersonic and counter-hypersonic capabilities were explicitly named as areas where "AUKUS partners will work together to accelerate development..."[279] Second, through the University Consortium for Applied Hypersonics (UCAH), the United States is working with many international universities from the UK and Australia.[280] While these partnerships are a good framework at the highest levels, there are significant opportunities that are not being used.

Bilateral Partnerships

The U.S. has bilateral partnerships with three countries related to hypersonic capabilities: Australia, Norway, and Japan.

Beginning in 2007, the U.S. has collaborated with Australia first on the HIFiRE program and more recently on its successor program, SCIFiRE.[281] The Hypersonic International Flight Research Experiment (HIFiRE) was a $54 million flight test program to develop hypersonic technologies, explore scramjet engine technologies, and, more recently, explore the flight dynamics of a Mach 8 hypersonic glide vehicle.[282] The Southern Cross Integrated Flight Research Experiment (SCIFiRE) program is focused on further developing hypersonic air-breathing technologies with the goal of reaching a point where conducting demonstration tests in the mid-2020s would be possible.[283] While these partnerships with Australia have been lauded as highly successful, they have faced some of the challenges that international partnerships often encounter. For example, in HIFiRE, some of the rockets needed for the flight tests contained asbestos, a material that could not be legally imported into Australia beyond a certain quantity.[284] A military exemption was made to solve the issue, but that did not come without significant paperwork and associated delay – in this case, nearly two years.[285] Unfortunately, collaboration with Australia has also faced challenges on the U.S. side. According to a working group participant, the program agreements (PAs) established by the U.S. DoD with Australia, were tied so tightly to a specific program, discipline, or application, that they impeded collaboration overall.

In early 2022, the U.S. announced that it would sign a new agreement with Japan to increase collaboration on the research and development of emerging technologies.[286] Among other technologies, the agreement focuses on advanced space systems and counter-hypersonic technologies.[287] In January 2023, DoD announced the signing of a "bilateral Memorandum of Understanding for Research, Development, Test and Evaluation Projects…" with the Japanese Ministry of Defense to improve defensive capabilities.[288] Among other projects, counter-hypersonics was listed as an area for collaboration. While counter-hypersonics is not the focus of this report, this is still an important international partnership worth noting.

Finally, beginning in 2019, the U.S. Department of Defense and Norwegian Ministry of Defense announced a partnership on "the development of an advanced solid fuel ramjet that could find use in supersonic and hypersonic weaponry."[289] The Tactical High-speed Offensive Ramjet for Extended Range, or THOR-ER, includes the U.S. Navy's Naval Air Warfare Center Weapons Division, China Lake, and the Norwegian Defence Research Establishment and industry partner Nammo Group.[290] By 2024, the goal was to "not only have a flight demonstration but be able to transition the technology to the warfighter."[291] In 2022, the solid fuel ramjet missile was first flight tested, thus meeting the Phase 1 objective of demonstrating the capabilities of jointly developed propulsion technologies in flight.[292] While this partnership is viewed as valuable both technically and politically, and should therefore continue, the unsecure nature of the Andøya test facility, including its proximity to a peer competitor, poses challenges.[293]

The existing bilateral and multilateral partnerships are a great step in the right direction. However, there are unused opportunities in these existing partnerships to help address current supply chain issues like lack of testing infrastructure, and resource dependency on adversaries.

ALLIED NEARSHORING

As discussed in Chapter 1, the U.S. is dangerously reliant on foreign adversaries for several critical raw materials relevant to hypersonic systems. While domestic onshoring might guarantee more secure sourcing, sometimes it is not economically feasible. An alternative might be allied nearshoring. Australia and Canada, two strong allies of the U.S., could potentially provide economically feasible alternatives for sourcing certain hypersonic materials. With large deposits of cobalt and rare earth elements, both countries provide an important alternative to China.[294]

Another place where international markets could play an important role in strengthening hypersonics supply chains is expanding the carbon fiber industry. According to a Bureau of Industry and Security (BIS) report, many companies want help from the U.S. government to identify global export opportunities.[295] As highlighted in Chapter 1, with the tremendous increase in demand for carbon fiber, the supplier base needs to grow and expand.

HYPERSONICS CHALLENGES OF THE CURRENT EXPORT CONTROL REGIME

A constant theme throughout the working group discussions is the challenge that the current export control regime poses to international collaboration, and especially efforts to strengthen hypersonics supply chains.[296] Export controls in the U.S. exist to protect American technological advantage and ensure U.S. national security. The International Traffic in Arms Regulations (ITAR) are administered to regulate the export of defense products, including a range of products from munitions to software to technical data and includes many components in the hypersonics supply chains. According to several working group participants, the fear of ITAR violations forces U.S. companies to seek domestic suppliers for the manufacturing of parts rather than pursue the export licenses required for foreign suppliers.[297] These licenses can be especially difficult to obtain for allied nations whose privacy laws protect employees from mandated passport submission. In the U.K., for example, labor laws permit firms to hire across Europe. While U.K. companies may explicitly not recruit from specific countries outside of the E.U., meeting the U.S. requirements for workforce verification poses a challenge. University partners outside of the U.S. face similar challenges as most programs tend to include disproportionately more foreign nationals. While universities have some procedures in place to safeguard access to protected information, the U.S. can still choose to deny export licenses if there is any concern of information leakage. While certain levels of export control are important to safeguard U.S. national security, some changes could be adopted to better facilitate international partnership on hypersonics.

Similarly, foreign companies are concerned about potentially losing control of their technology due to legal agreements that give first or sole rights to the U.S. government in government-funded development projects that result in intellectual property. Companies often take a protectionist approach by turning their focus to acquiring patents in order to protect their sensitive information.

Finally, in addition to strict U.S. export regulations, the language in some DoD defense acquisition contracts can be uninviting to allied nations.[298] Contracts typically include prohibitions against foreign participation, requiring materials and subcomponents to be sourced domestically—usually without exception. There is often a requirement for programs to be U.S. in origin and performed only by U.S. citizens. Again, in certain situations, prohibition against foreign participation is appropriate for national security reasons. However, the U.S. should look for opportunities where international cooperation on hypersonics can be strengthened.

CLASSIFICATION CHALLENGES

While it is clearly important that hypersonic technologies be protected, it was suggested in working group discussions that the U.S. government tends to overclassify information pertaining to hypersonic systems. This issue is more pervasive than just hypersonics, but the implications for international cooperation regarding hypersonics are especially stark. Classification exists to protect the most sensitive DoD capabilities, information, technologies, and operations. At the highest levels of classification, Special Access Programs (SAPs) were originally established for defense acquisitions (among other things) as they safeguard classified information with additional access requirements that exceed those normally required for information at the same classification level.[299] Due to the sensitive nature of SAPs, it is uncommon for non-American citizens to be granted access. In fact, only the Secretary or Deputy Secretary of Defense may approve access of foreign nationals to DoD SAPs.[300] This can make it extremely difficult for even the closest U.S. allies and partners to participate in these technological areas of opportunity. As a result, allied nations feel shut out of key defense innovation programs which puts a strain on bilateral relationships with the U.S.

SUMMARY

Overall, the U.S. currently has strong international partnerships when it comes to hypersonics. However, there are opportunities to improve upon and expand these partnerships to help strengthen hypersonics supply chains going forward.

RECOMMENDATIONS

1. The U.S. should work with Australia and Canada to increase mining and processing operations for cobalt, rare earth elements, and nickel.

With China dominating the rare earth element markets, the U.S. needs to look elsewhere to diversify these supply chains.[301] Australia, as a close ally, has large deposits of REEs, cobalt, and nickel. Canada, another close ally, has the 6th largest known reserve of cobalt and has recently begun increasing mining operations for the material.[302] As the demand for cobalt, nickel, and rare earths potentially increases due to demand for EVs and batteries, the U.S. should look to allies to increase mining operations. Like carbon fiber, the demand from hypersonics for these materials is only a small slice of the market. Thus, in order for supply to keep up with increasing demand and to decrease adversary dependency in hypersonics supply chains, the U.S. should seek to expand mining and processing operations in Australia and Canada.

2. The U.S. DoD should look for opportunities to increase international partnerships to address insufficient testing infrastructure.

As discussed in Chapter 2, the present-day hypersonics testing infrastructure is insufficient. While significant investments are needed to modernize and increase *domestic* testing capacity, using potential or actual infrastructure in allied and partner nations could remedy the shortfalls in the long-and short-term. DoD already has a strong partnership with Australia in this regard. This partnership must be maintained and expanded, where appropriate. While current Canadian hypersonics testing infrastructure is limited, the massive expanses of open land in the north could be used for an overland flight-testing corridor. The Department of Defense should conduct a feasibility study for an overland flight-testing corridor in Northern Canada. If it proves feasible, the DoD should then solicit industry investment and a cost-sharing agreement with the Canadian Ministry of Defence to begin construction. While this solution can help remedy testing shortfalls in the long-term, short-term recommendations are also needed. Given the current THOR-ER partnership, DoD should expand this partnership in a similar way, using Norwegian testing infrastructure, such as the Andøya test facility for S&T purposes, but being cognizant of existing security concerns. Finally, DOD should look for opportunities with other partners and allies to increase international partnerships to address insufficient testing infrastructure.

3. The U.S. Department of Defense and Australian Ministry of Defence should establish an overarching program agreement to expedite hypersonics collaboration across the board.

Through the HIFiRE and SCIFiRE programs, Australia has shown itself a capable partner in hypersonics collaboration. However, the partnership could be enhanced by an overarching program agreement (PA), so a new agreement does not have to be negotiated each time the countries want to collaborate on a program. By eliminating potential delays caused by negotiation, and expanding the number of disciplines included, this agreement could facilitate substantial progress in hypersonics development. This overarching agreement should allow for collaboration on major hypersonic disciplines including airbreathing propulsion, guidance, navigation, and control (to includes seekers and sensors), high speed flight sciences, vehicle design and concept development, warheads, high temperature materials, ground testing and evaluation, modeling and simulation, and even counter-hypersonics (to include C2BMC, interceptors, and radars/sensors). Through collaboration in specific hypersonics programs, as well as access to a broader array of testing infrastructure, the U.S.-Australian partnership could be an invaluable asset to mitigate key supply chain concerns.

4. Committee on Foreign Investment in the U.S. (CFIUS) investigations should be prioritized using a four-tiered system for organizing supply chain risk.

CFIUS is an interagency committee authorized to review the national security implications of foreign investment in U.S. companies or operations. CFIUS's duties have become increasingly imperative as the Chinese government has expanded foreign investment activities. The CFIUS timetable for investigations includes a 45-day review period, another 45-day investigation period, and a 15-day presidential review period.[303] According to the working group participants, this process is lengthy and does not consider the relationship of the country where the company is located. While an in-depth study should be conducted on the issue, the working group participants recommended the following. To instill a more efficient process, CFIUS investigations could be organized into four tiers. The first tier is the AUKUS countries, in which there is a shared approach to export controls. The second tier is the NATO countries, in which there are more restrictions for sharing technology and CFIUS acts on a case-by-case basis. More sensitive technology is restricted under ITAR. The third tier consists of countries that are neither allied nor adversarial. These countries likely necessitate a more thorough investigation than AUKUS or NATO. The fourth tier consists of countries deemed adversarial to the U.S., where technology is not sold at all. These countries should be investigated to the full extent of CFIUS's authority.

5. The Department of Commerce could assist domestic carbon fiber companies by publishing an annual list of recommendations for global export opportunities.

As discussed in Chapter 1, a shortage of carbon fiber suppliers negatively impacts hypersonics supply chains and must be addressed if the supply chains will support the increased scale of fielded hypersonic systems. Given that the U.S. is one of the top suppliers of carbon fiber in the world, one way to increase domestic production is to increase access to global customers. Several years ago, the Commerce Department's BIS published the results of industry surveys in which the majority of respondents wanted help from the U.S. government to identify global export opportunities. This is one way that the U.S. government could assist in growing the carbon fiber supply base, and thus strengthening hypersonics supply chains.

CONCLUSION

Hypersonics will likely play an increasingly critical role in the future of U.S. defense. Because of the significant advantages that hypersonic systems bring, and because of the relatively advanced state of Russian and Chinese hypersonic programs, these weapons will maintain their place in the spotlight of strategic competition. In recognition of this, it is vital that government, industry, and academia be aware of the many vulnerabilities that exist within the hypersonics supply chains. If left unaddressed, these vulnerabilities could compromise the United States' ability to effectively field hypersonic weapons. The conflict in Ukraine has demonstrated how quickly the demands of war can drain the arms inventories of supposedly well-prepared combatants. The U.S. must learn from this example and preempt potentially detrimental shortages.

The issues in the U.S. hypersonics supply chains have been building for years. The lack of a clear demand signal has severely impaired the future stability of the supply chain and will continue to jeopardize key national security initiatives until adequately addressed. Ultimately, it will take years of hard work before the system can rebalance and, until then, challenges will still exist. Unfortunately, there are no quick fixes. However, there are many steps government, industry, and academia can take to strengthen hypersonics supply chains for the future.

DoD must provide a clear and constant demand signal for hypersonic systems. This, by far, is the most important step the government can take to ensure secure, healthy hypersonics supply chains. Furthermore, DoD should request and Congress should appropriate reliable funding for hypersonic systems while also taking action to restore critically depleted stockpiles of strategic materials. DoD must also pursue expanded cooperation with allies and partners, many of which can help to secure supplies of critical resources and to develop reliable and much-needed testing infrastructure. America's allies and partners are perhaps its greatest asset and one which its competitors almost universally lack. Failing to take advantage of this enormous resource would be an inexcusable blow to U.S. national security objectives.

For industry, there are numerous opportunities for growth and investment. From using additive manufacturing and digital engineering to cut costs, to increasing awareness of counterintelligence threats, to investing in new mines and carbon fiber production facilities, industry can begin today to secure supply chains for tomorrow. Considering these opportunities, industry needs a large, well-equipped workforce to fuel its innovation. Academia is crucial for educating the hypersonic workforce of the future and can also contribute to expanding testing infrastructure.

Partnerships between government, industry, and academia provide the greatest potential for overcoming the vulnerabilities of the hypersonics supply chain. However, action must be taken today. Each of these changes will take time but are crucial to securing hypersonics supply chains for years to come.

ANNEX A – ADDITIONAL REFERENCES

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/.

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.

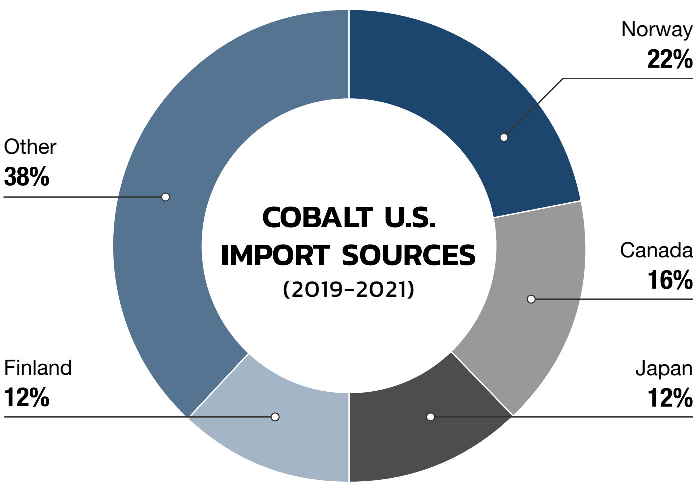
TABLE A-6. INDUSTRY/ACADEMIC RESEARCH-RELATED FACILITIES

Facility	Capability	Location
CUBRC Large Energy National Shock (LENS)-1/-II/-XX Tunnels	LENS 1: 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
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.

CRITICAL RAW MATERIALS REFERENCE CHARTS



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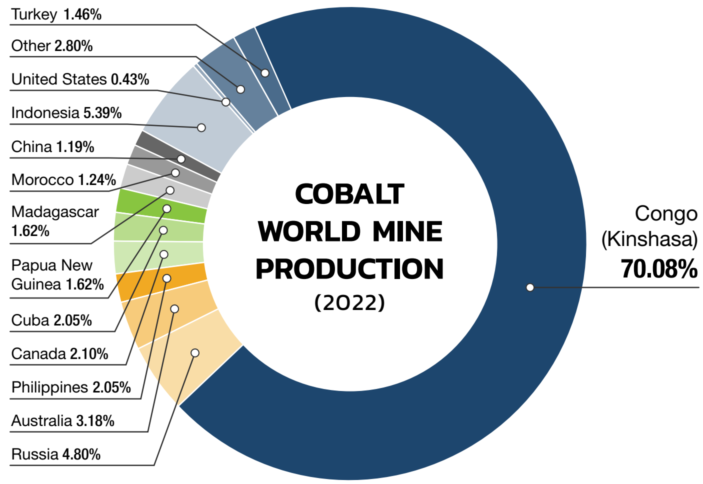

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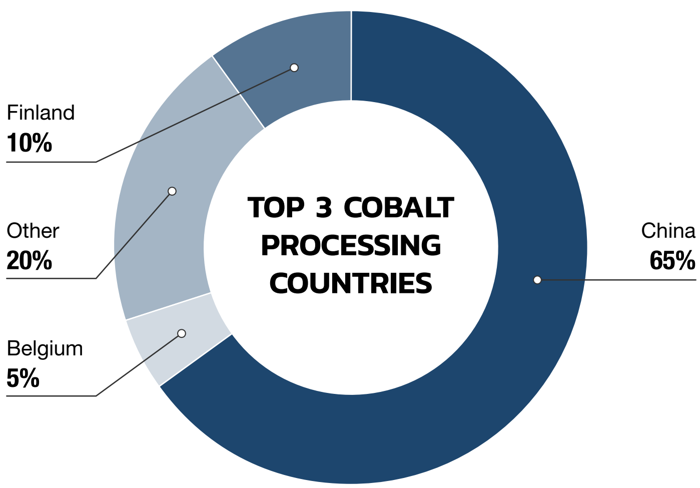

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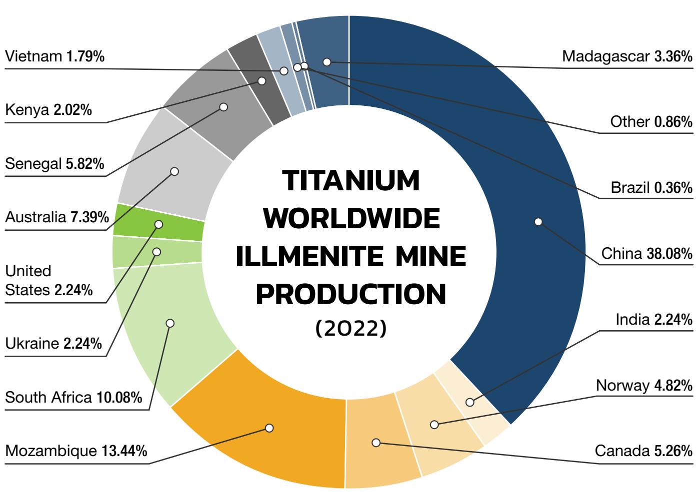

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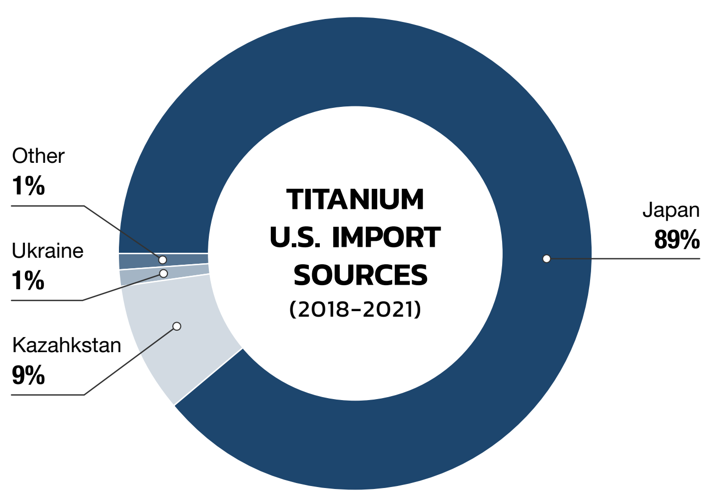

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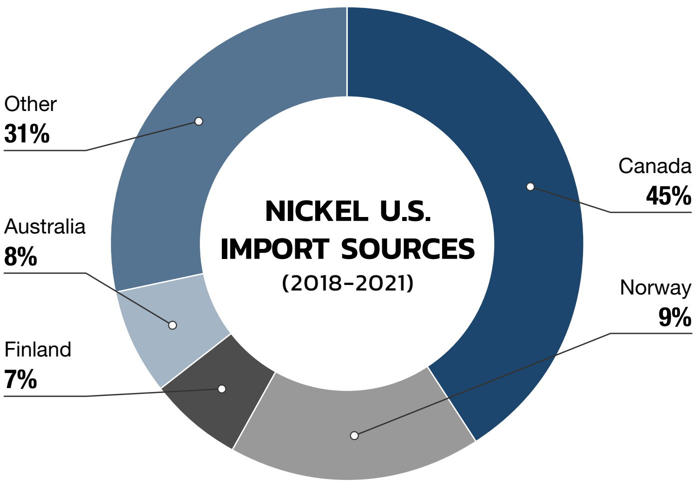

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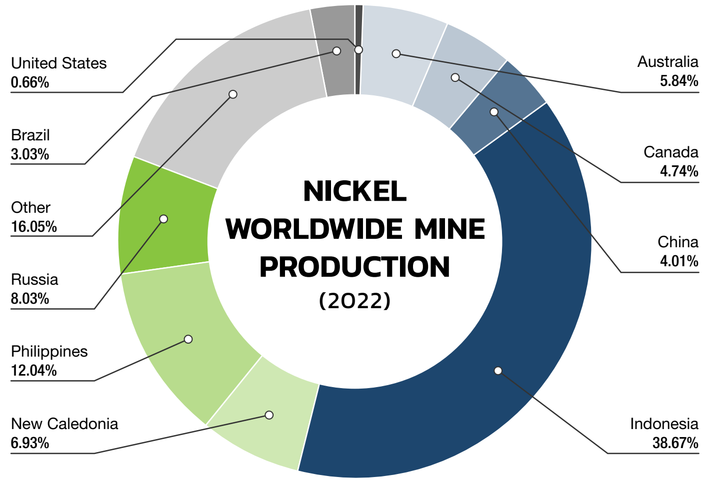

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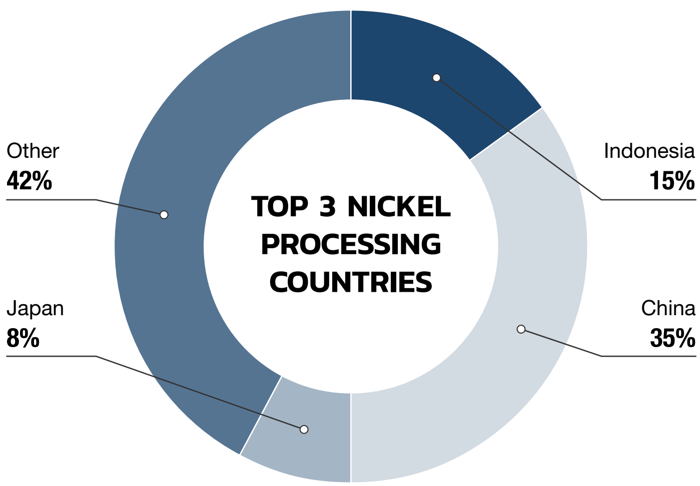

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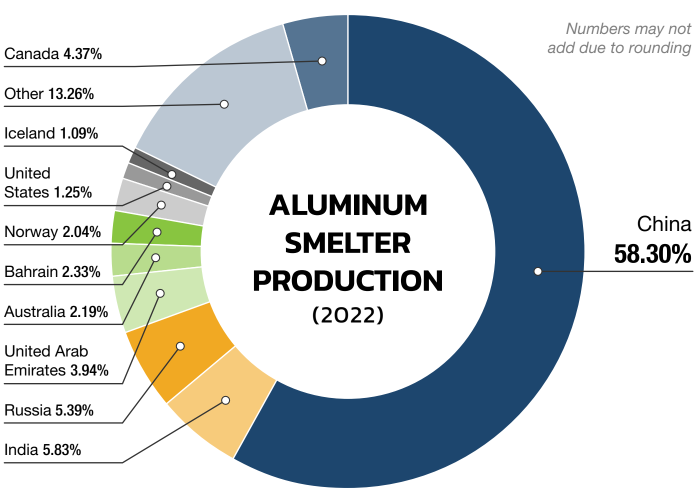

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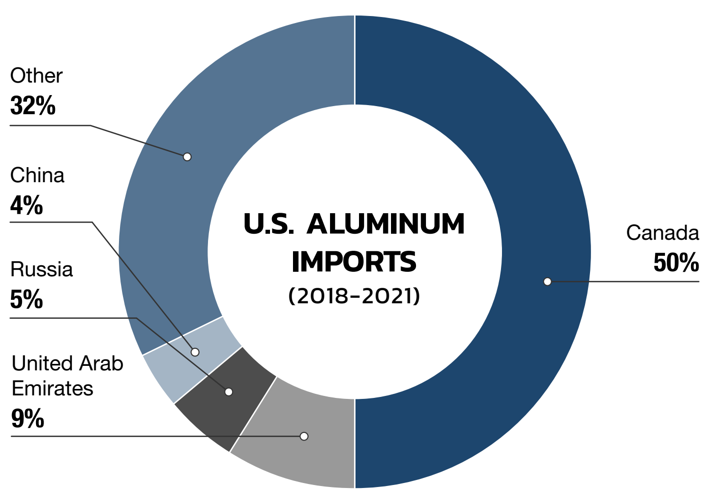

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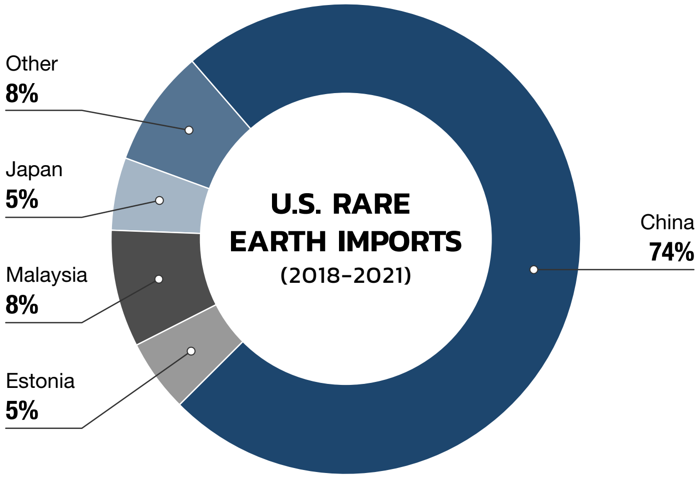

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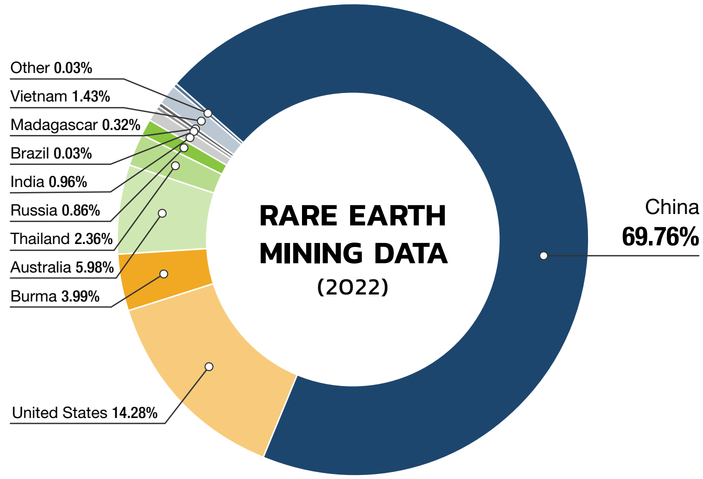

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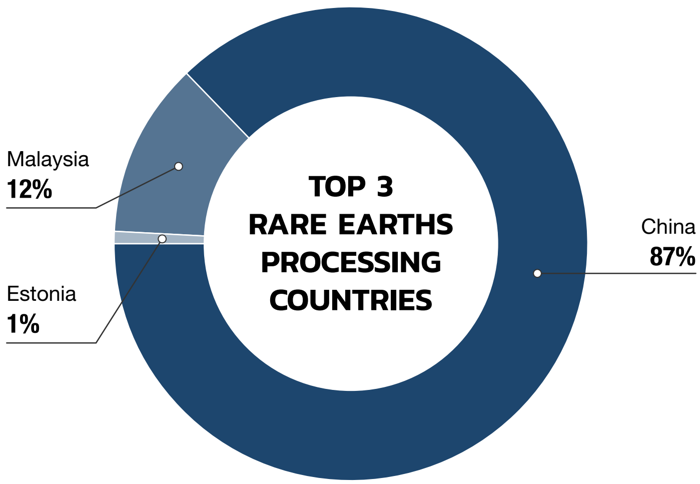

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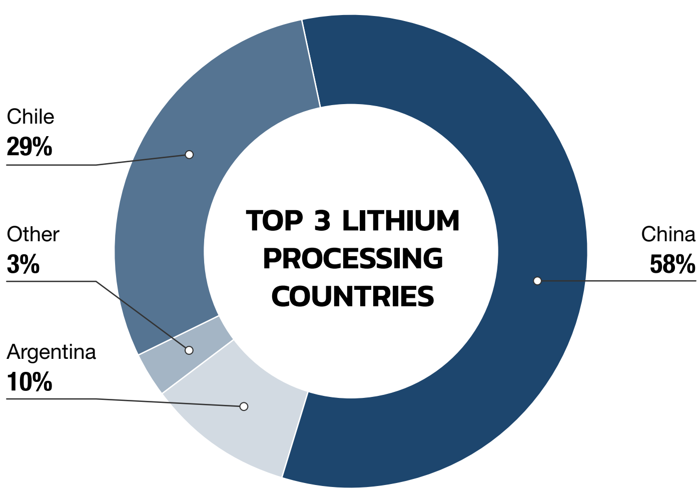

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ANNEX B – FUNDING PRIORITIES

Given the finite resources of the U.S. government, it may not be feasible to simultaneously implement the totality of funding increases recommended by this report. In light of this reality, below is a ranking of recommendations that require expanded funding. The top rankings are those deemed most critical to the efficacy of hypersonics supply chains.

1. The Department of Defense should provide a consistent and clear demand signal to industry by treating certain hypersonic programs as traditional Programs of Record and utilizing multi-year contracts.
2. DoD should increase the hypersonics flight test schedule.
3. Additional testing infrastructure should be funded jointly by DoD and Industry at appropriate academic institutions in order to help replace aging testing infrastructure.
4. Working together, Congress and the Department of Defense should reinforce the National Defense Stockpile of strategic minerals.
5. DoD should address major cybersecurity risks at the low-to-mid-tier levels of the hypersonics supply chains by creating a "bug bounty" program for small government contractors working on hypersonics.
6. The U.S. Government should continue to fund existing programs to track intellectual property (IP) theft within defense emerging technology supply chains, including hypersonics. Furthermore, the U.S. government should continue to develop new systems to track the entire range of IP theft affecting the DIB.
7. DoD should request additional funding for the University Consortium for Applied Hypersonics (UCAH) to focus on hypersonic leap-ahead technologies

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