MINERAL SUPPLY CHAINS AND SPACE ASSETS

Mitigating Manufacturing Dependencies

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Space is an increasingly competitive military domain. Both the United States and China seek to build and deploy significant numbers of space assets, most of which are mineral-intensive. The mineral compositions of three important space assets—satellites, direct-ascent antisatellite weapons, and rocket bodies—require the United States to import minerals, particularly from China, for their construction. Consequently, the US space industry, and thus the US government, faces the associated risks of supply chain disruptions that can restrict mineral availability and cause price volatility, negatively impacting space asset production. This article proposes three policies to mitigate such risks to the mineral supply chains.

Space is an increasingly important—and contested—military domain.[1] Most of the growing number of space assets being built and deployed by the United States and China are mineral-intensive. Yet US supply chains for space assets depend heavily on mineral imports, often from China. Mechanisms such as foreign export controls can restrict mineral availability and cause price volatility, thus negatively impacting US manufacturing of space assets.

To mitigate import disruption risks to the supply chains of these assets, the US government—with the US Space Force as the primary coordinator—should adopt the following policies: stockpile minerals vital to US space assets, similar to the Strategic Petroleum Reserve or the National Defense Stockpile; provide concessional financing for US space companies to sign long-term, fixed-price mineral offtake agreements;

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1. Elbridge Colby, *From Sanctuary to Battlefield: A Framework for a US Defense and Deterrence Strategy for Space* (Washington, DC: Center for New American Security, January 2016), https://www.cnas.org/.

and impose environmental and labor (E&L) tariffs on mineral imports produced in countries that do not adhere to equivalent US standards. This last policy would incentivize US space companies to source minerals domestically and from partner countries with high environmental and labor standards.

The Mineral-Intense Space Competition

Today, space is a competitive domain to a degree not seen since the space race between the United States and the Soviet Union in the 1950s.[2] In fact, the US military has officially declared space a warfighting domain.[3] In February 2024, Commander of US Space Command General Stephen N. Whiting warned that the space activities of China are augmenting its efforts to oust US military influence from the first island chain—roughly comprising Japan, Taiwan, part of the Philippines, and Indonesia—and the second island chain, which mainly includes Guam, the Northern Mariana Islands, and Palau.[4]

Indeed, an invasion of Taiwan by China—America's "pacing threat"—would likely feature space warfare and perhaps even the use of high-altitude electromagnetic pulse weapons to impair Taiwan's military defenses.[5] Possibly foreshadowing China's use of space warfare before an invasion of Taiwan, the Russian government hacked the US satellite company Viasat, which Ukraine's military relied on for communication, command, and control, on the eve of its 2022 invasion of Ukraine.[6]

If a Chinese invasion of Taiwan leads to a broader conflict with the United States, China would likely target US satellites as well. A recently revised People's Liberation Army doctrinal publication noted how the combat effectiveness of the US Air Force drops significantly without satellites.[7] Further, one 2022 analysis warns, "The People's Liberation Army has the incentives and capabilities to conduct preemptive attacks against US space

2. Charles Pope, "Raymond Praises Space Force Achievements and Purpose While Noting Ongoing Threats, Challenges," US Space Force, April 5, 2022, https://www.spaceforce.mil/.

3. Pope; Everett C. Dolman, "Space Is a Warfighting Domain," *Æther: A Journal of Strategy and Airpower* 1, no. 1 (Spring 2022), https://www.airuniversity.af.edu/; C. Todd Lopez, "Shanahan: Next Big War May Be Won or Lost in Space," US Department of Defense [DoD], April 9, 2019, https://www.defense.gov/; and Lloyd J. Austin III, "Senate Armed Services Committee Advance Policy Questions for Lloyd J. Austin, Nominee for Appointment To Be Secretary of Defense," US Senate Committee on Armed Services, January 19, 2021, 56, https://www.armed-services.senate.gov/.

4. Patrick Tucker, "Chinese Space, Nuclear Development Is 'Breathtakingly Fast,' DOD Officials Warn," Defense One, February 29, 2024, https://www.defenseone.com/; Yusuke Kawachi, "The Case of Japanese Land Power in the First Island Chain," *War on the Rocks*, February 13, 2023, https://warontherocks.com/; and Tom O'Connor and Naveed Jamali, "How US Plans for a Faraway Pacific War While China Plots to Disrupt It," *Newsweek*, April 20, 2023, https://www.newsweek.com/.

5. Gabriel Honrada, "Electric Shield: Taiwan Girding for a Chinese HEMP Attack," *Asia Times*, November 2, 2023, https://asiatimes.com/.

6. Patrick Howell O'Neill, "Russia Hacked an American Satellite Company One Hour before the Ukraine Invasion," *MIT Technology Review*, May 10, 2022, https://www.technologyreview.com/.

7. *In Their Own Words: Science of Military Strategy 2020* (Montgomery, AL: China Aerospace Studies Institute, January 2022), 379, https://www.airuniversity.af.edu/.

assets," including satellites.[8] As evidenced by its antisatellite test in 2007, China has also shown a willingness to use antisatellite weapons, regardless of the resulting space debris.[9] Thus, US-China space warfare could involve mineral-intensive space assets.

Mineral Compositions of Space Capabilities

The most common materials in US space assets—including satellites, direct-ascent antisatellite (DA-ASAT) weapons, and rocket bodies—are metallic materials, even more so than composite and ceramic materials.[10] Metallic materials with high strength-to-weight ratios, such as aluminum, titanium, and stainless steel, help reduce launch costs and increase payload capacity.[11] These minerals must also withstand extreme temperature fluctuations and are often alloyed together, providing additional performance benefits.[12]

Satellites

In a US-China conflict, satellites would function in an intelligence, surveillance, and reconnaissance role for both combatants, as well as an enabler of precision-guided missiles.[13] Possibly in anticipation of conflict with China in the space domain, the US military is creating satellite redundancy by launching large satellite constellations. The US Space Force's Space Development Agency aims for 1,000 satellites in orbit by 2026, and the US National Reconnaissance Office intends to "quadruple" its satellite fleet by 2033.[14]

Given the mineral intensity of satellites, these deployment targets have significant mineral demand implications. As one study notes, "The [satellite] structure mainly consists of [aluminum]-alloys, [titanium]-alloys, or stainless steel," adding that solar

8. Jiemin Hou, "Offensive Defense: People's Liberation Army Logic of Preemption in Space," *Æther: A Journal of Strategic Airpower & Spacepower* 1, no. 4 (Winter 2022): 12, 19, https://www.airuniversity.af.edu/.

9. Theresa Hitchens, "Debris from ASAT Tests Creating 'Bag Neighborhood' in Low Earth Orbit: Analyst," Breaking Defense, June 16, 2023, https://breakingdefense.com/.

10. Biliyar N. Bhat, "Aerospace Materials Characteristics," in *Aerospace Materials and Applications*, ed. Biliyar N. Bhat (Reston, VA: American Institute of Aeronautics and Astronautics, 2018), 1, https://ntrs.nasa.gov/.

11. Miria M. Finckenor, "Materials for Spacecraft," in *Aerospace Materials and Applications*, 8, https://ntrs.nasa.gov/.

12. Paul Gradl et al., "Advancement of Extreme Environment Additively Manufactured Alloys for Next Generation Space Propulsion Applications," *Acta Astronautica* 211 (2023): 483–85, https://doi.org/; and Finckenor, 9.

13. *2022 Challenges to Security in Space: Space Reliance in an Era of Competition and Expansion* (Washington, DC: Defense Intelligence Agency, February 1, 2022), 9, https://www.dia.mil/.

14. Ramin Skibba, "The Space Force Is Launching Its Own Swarm of Tiny Satellites," *Wired*, August 14, 2023, https://www.wired.com/; and Theresa Hitchens, "NRO Plans 10-Fold Increase in Imagery, Signals Intel Output," Breaking Defense, October 10, 2023, https://breakingdefense.com/.

arrays contribute substantially to satellite mass. These arrays are predominantly composed of silicon, silver, aluminum, glass, germanium, and gallium (fig. 1).[15]

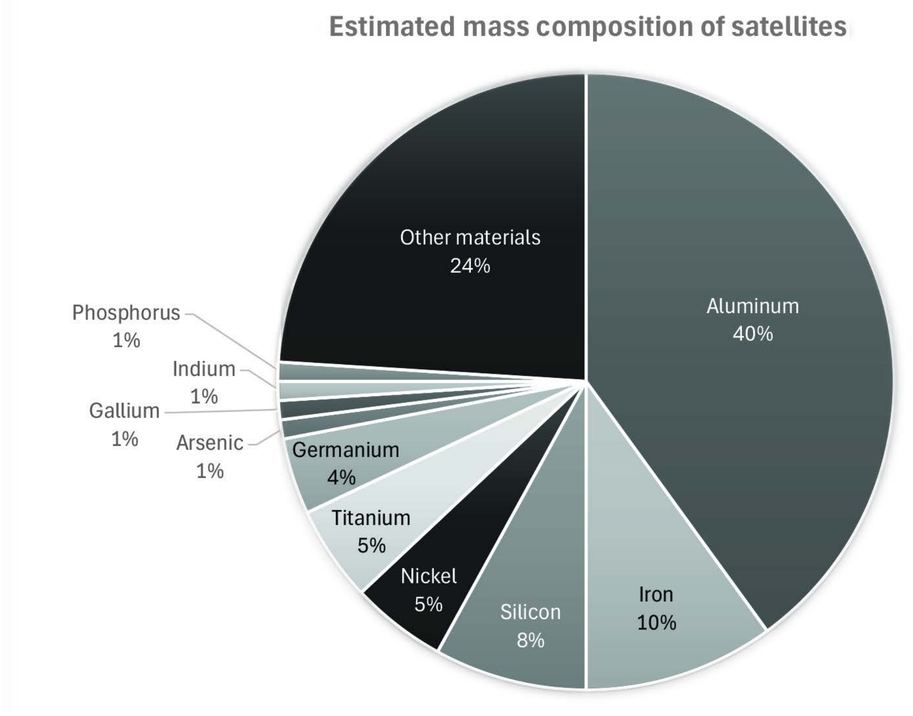

Figure 1. Estimated mass composition of satellites based on 2020 study[16]

Concerningly, the United States in 2023 had a high net import reliance, or the imports' share of domestic consumption, for many of these minerals: over 95 percent for titanium sponge metal, 57 percent for nickel, more than 50 percent for germanium—which the United States imports mainly from China—nearly 50 percent for silicon, and 44 percent for aluminum.[17] The United States also had a net import reliance of 100 percent for arsenic, 100 percent for gallium, 100 percent for indium, and 14 percent for phosphate rock.[18] Thus, it is highly dependent on imports of minerals necessary in satellites, exposing these mineral supply chains to disruption and cost risks.

15. Leonard Schulz and Karl-Heinz Glassmeier, "On the Anthropogenic and Natural Injection of Matter into Earth's Atmosphere," *Advances in Space Research* 67, no. 3 (2021), arXiv, August 29, 2020, 11, https://doi.org/.

16. Schulz and Glassmeier, 11.

17. Adam M. Merrill, "Aluminum," in *Mineral Commodities Summaries 2024* (Reston, VA: US Department of the Interior, US Geological Survey [USGS], January 2024), 32, https://doi.org/; Michele E. McRae, "Nickel," 124; Joseph Gambogi, "Titanium and Titanium Dioxide," 186; Emily K. Schnebele, "Silicon," 160; and Amy C. Tolcin, "Germanium," 80.

18. Micheal W. George, "Arsenic," in *Mineral Commodities Summaries,* 36; Brian W. Jaskula, "Gallium," 74; Andrew A. Stewart, "Indium," 90; and Stephen M. Jasinski, "Phosphate Rock," 134.

Direct-Ascent Antisatellite Weapons

Direct-ascent antisatellite weapons are an important counterspace capability. In a potential conflict, both China and the United States could target each other's satellites.[19] For example, the US military could use DA-ASAT weapons to target Chinese military satellites, hindering China's invasion effort and its possible long-range missile strikes on US forces in the Western Pacific.[20]

The US government currently has a self-imposed testing moratorium on destructive DA-ASAT weapons and reportedly prefers nonkinetic methods to disable adversarial satellites, but these weapons could prove highly effective among the available options in a US-China conflict.[21] While the US military does not have explicit DA-ASAT weapons, the Standard Missile-3 (SM-3) has demonstrated a DA-ASAT role as part of the Aegis Ballistic Missile Defense system. The Ground-based Midcourse Defense system and the Terminal High Altitude Area Defense system likely have similar DA-ASAT capabilities.[22]

The mineral-intensive SM-3 uses an aluminum guidance section, a stainless steel shell for third-stage components, and a graphite bismaleimide nose cone, which features an underlying thin molybdenum coating and a blunted titanium nose tip.[23] The SM-3 also uses rhenium for components exposed to high temperatures.[24]

For several of these minerals, the United States relies heavily on imports. For example, in 2023 it had an estimated net import reliance of 60 percent for rhenium and 100 percent for natural graphite, which it imports mainly from China.[25] Consequently, if the United States increases SM-3 production due to military expansion or

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19. James A. Lewis, "Reconsidering Deterrence for Space and Cyberspace," in *Anti-satellite Weapons, Deterrence and Sino-American Space Relations*, ed. Michael Krepon and Julia Thompson (Washington, DC: Stimson Center, September 2013), 75, https://www.stimson.org/.

20. Mark A. Gubrud, "Chinese and US Kinetic Energy Space Weapons and Arms Control," *Asian Perspective* 35, no. 4 (2011): 625–26, http://www.jstor.org/.

21. Ching Wei Sooi, *Direct-Ascent Anti-Satellite Missile Tests: State Positions on the Moratorium, UNGA Resolution, and Lessons for the Future* (Broomfield, CO: Secure World Foundation and Swiss Existential Risk Initiative, October 2023), iii, https://swfound.org/; Laura Grego, "The Anti-Satellite Capability of the Phased Adaptive Approach Missile Defense System," *Federation of American Scientists* (Winter 2011): 4, https://pubs.fas.org/; and Gubrud.

22. Laura Grego, *A History of Anti-Satellite Programs* (Cambridge, MA: Union of Concerned Scientists, January 2012), 12, https://www.ucsusa.org/; and "Anti-Satellite Capability."

23. Gary A. Sullins, "Exo-atmospheric Intercepts: Bringing New Challenges to Standard Missile," *Johns Hopkins APL Technical Digest* 22, no. 3 (2001): 271, 273, https://secwww.jhuapl.edu/; and Scott D. Robinson, "Navy Theater-Wide Defense AEGIS LEAP Intercept (ALI)/STANDARD Missile 3 (SM-3) Flight Test Program Overview" (presentation, 6th Annual AIAA/BMDO Technology Readiness Conference, San Diego, CA, August 21, 1997), 6–7, https://apps.dtic.mil/.

24. National Center for Excellence in Metalworking Technology, *2003 Annual Report: Providing Metalworking Solutions to Enable Defense Transformation* (Mechanicsburg, PA: Concurrent Technologies Corporation, 2003), 9, https://apps.dtic.mil/.

25. Désirée E. Polyak, "Rhenium," in *Mineral Commodities Summaries*, 146; and Andrew A. Stewart, "Graphite (Natural)," 84.

munition attrition in a US-China conflict, these production lines could face disruption risks from Chinese mineral export controls or contested shipping routes.

Rocket Bodies

Rocket bodies are vital in enabling components in space and counterspace capabilities, powering satellites to their appropriate orbits and DA-ASAT weapons to their intended targets. A rocket body—which consists of a propulsion tank, engines, an internal and external structure, and a guidance and control system—must withstand extreme temperatures and pressure. Therefore, rocket bodies contain various alloys, including minerals such as aluminum, copper, hafnium, and lithium (fig. 2).[26]

Propulsion tanks are commonly made of AA2219 aluminum alloy; however, SpaceX's Super Heavy rocket booster consists of 300-series stainless steel.[27] For rocket engines, common alloys are nickel alloys such as Inconel 600 and Inconel 718, but SpaceX's Raptor rocket engines use a proprietary nickel alloy called SX500.[28] Wiring in rocket bodies is usually copper, while feedlines and other components are generally made of stainless steel, aluminum alloys, and titanium alloys.[29] Lastly, rocket nozzle extensions are often made of C-103 alloy, which consists of niobium, hafnium, and titanium.[30]

26. Daniel M. Murphy et al., "Metals from Spacecraft Reentry in Stratospheric Aerosol Particles," *Proceedings of the National Academy of Sciences of the United States of America* 120, no. 43 (2023): 2–3, https://doi.org/.

27. Rupendra Brahambhatt, "Why SpaceX's Starship Mega-Rocket Looks Unlike Anything the Company Has Ever Built Before," *Business Insider*, April 20, 2023, https://www.businessinsider.com/; and see Jim Rauf, "SpaceX 6: Starship and Super Heavy Booster" (lecture slides, University of Cincinnati, OH, 2023), 5, https://www.uc.edu/.

28. Schulz and Glassmeier, "Anthropogenic," 11; and Trevor Sesnic, "Raptor 1 vs Raptor 2: What Did SpaceX Change?," Everyday Astronaut, July 14, 2022, https://everydayastronaut.com/.

29. Daniel M. Murphy et al., "Metals from Spacecraft Reentry," 3; and Schulz and Glassmeier, 9.

30. Murphy et al., 3; and Omar R. Mireles et al., "Additive Manufacture of Refractory Alloy C103 for Propulsion Applications" (presentation, 2020 AIAA Propulsion and Energy Forum, August 24–26, 2020, virtual), 2, https://ntrs.nasa.gov/.

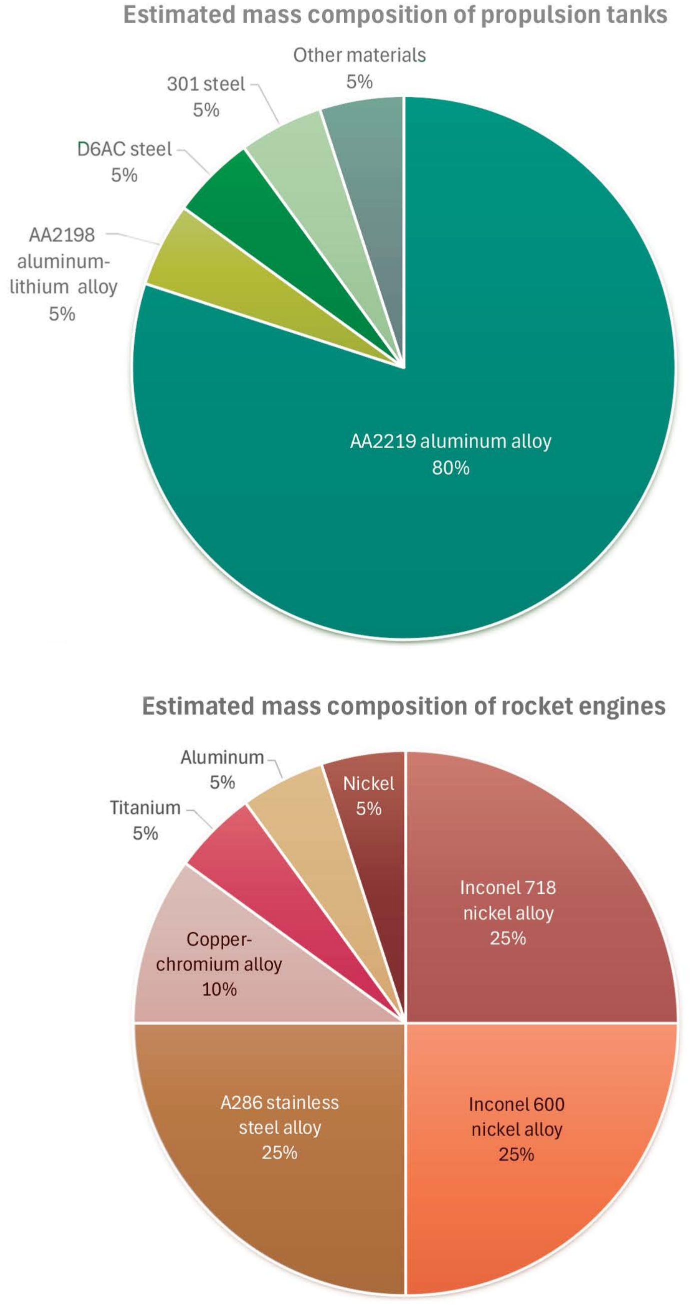

Figure 2. Estimated mass composition of propulsion tanks and rocket engines based on 2020 study[31]

31. Schulz and Glassmeier, "Anthropogenic," 9.

The United States relies on imports for these alloying elements as well, such as hafnium and niobium, subjecting them to the risks of supply chain disruption. Only two US companies produce hafnium metal; consequently, some hafnium comes from China and Russia.[32] With the limited supply of hafnium metal and its soaring demand in aerospace alloys, prices of this metal have increased dramatically, posing risks to the downstream production of space assets.[33]

Unlike with hafnium, the United States relies entirely on imports for its niobium consumption.[34] While America imports most of its niobium from Brazil, Chinese companies have ownership stakes in Brazilian production: a Chinese consortium has a 15 percent stake in Brazil's largest niobium producer, and a Chinese company—a subsidiary of CMOC—is the second largest niobium producer in Brazil.[35] As a result, the United States risks disruption of the mineral imports necessary to manufacture rocket bodies.

Mineral Supply Chain Risks

Russia and China, as major mineral producers, are linchpins in space asset supply chains. For example, Russia is a major global producer of titanium sponge, and the US government—while it has restricted imports of other Russia-produced minerals—has partly avoided restricting imports of Russian titanium given the aerospace industry's dependence on this supply.[36] During the Cold War, the Soviet Union was the world's largest titanium metal producer, and the US Central Intelligence Agency secretly procured Soviet titanium via third-party countries for Lockheed Martin when the company was building the SR-71 reconnaissance aircraft to spy on the Soviet Union.[37]

China has been recognized as a twenty-first century "mineral power" surpassing the United States, with its significant access to secure mineral supplies correlated with

32. Nedal T. Nassar, Elisa Alonso, and Jamie L. Brainard, *Investigation of US Foreign Reliance on Critical Minerals: US Geological Survey Technical Input Document in Response to Executive Order No. 13953 Signed September 30, 2020* (Reston, VA: USGS, December 7, 2020), 37, https://pubs.usgs.gov/; and Joseph Gambogi, "Zirconium and Hafnium," in *Mineral Commodities Summaries*, 204.

33. Gambogi, 205.

34. Chad A. Friedline, "Niobium (Columbium)," in *Mineral Commodities Summaries*, 126.

35. Abraham J. Padilla, "Niobium," in *2018 Minerals Yearbook* (Reston, VA: USGS, October 2021), 52.2, https://pubs.usgs.gov/; "Our History," CBMM [Companhia Brasileira de Metalurgia e Mineração], accessed April 16, 2024, https://cbmm.com/; and Jake Spring, "Hands Off Brazil's Niobium: Bolsonaro Sees China As Threat to Utopian Vision," Reuters, October 25, 2018, https://www.reuters.com/.

36. Adam Taylor, "Two Years after Start of Ukraine War, Russian Titanium Keeps Flowing to West," *Washington Post*, March 21, 2024, https://www.washingtonpost.com/; and Daniel Flatley and Jack Farchy, "Russian Metal Hit with Sanctions As US Blocks Deliveries to LME," Bloomberg, April 12, 2024, https://www.bloomberg.com/.

37. *The Soviet Titanium Industry and Its Role in the Military Buildup: A Research Paper* (Washington, DC: US Central Intelligence Agency, March 1985), iii, 1, https://www.cia.gov/; and Maya Carlin, "Titanium from Russia Was the Secret Ingredient in the SR-71 Blackbird," *National Interest*, December 3, 2023, https://nationalinterest.org/.

considerable military capabilities.[38] China is the world's dominant mineral producer and refiner and thus the key bottleneck in the mineral supply chain for space assets. To illustrate, China's Xinjiang Uyghur Autonomous Region produces about 45 percent of the world's polysilicon for crystalline silicon photovoltaic modules, whose space-grade versions power some space assets.[39] State support, especially financing, to Chinese mineral companies has helped China achieve this mineral dominance.

Importantly, the Chinese government financially supports not only domestic mineral projects but also overseas mineral projects.[40] For instance, Chinese state development banks (China Development Bank, Export-Import Bank of China) and Chinese state-owned commercial banks (Bank of China, Industrial and Commercial Bank of China) have financed coal-fired power plants at the Indonesia Morowali Industrial Park, which produces significant volumes of nickel-containing materials such as stainless steel.[41] Ultimately, China's influence over global production for many minerals gives it leverage over the supply chains of US space assets.

With its high mineral import dependence, the US space industry faces the associated risks of import disruptions such as export controls, which can restrict mineral availability and cause price volatility and which has stymied the production of US space assets. For example, China imposed export controls on gallium, germanium, and graphite in 2023, which significantly decreased these exports.[42] These minerals are used as inputs in space assets: gallium is used in semiconductors and aerospace applications; germanium is used in semiconductors as well as solar cells for satellites; and graphite is used in batteries, powdered metals, and refractory applications.[43]

US supply chains also face import disruption risks from other variables as well, including natural disasters, host government issues, and contested shipping routes. For instance, the attacks by Houthi rebels in Yemen on commercial ships transiting the Red Sea in late 2023 and early 2024 disrupted downstream supply chains such as automotive

38. Gregory Wischer and Morgan Bazilian, "The Rise of Great Mineral Powers," *Journal of Indo-Pacific Affairs* 7, no. 2 (March-April 2024), https://www.airuniversity.af.edu/.

39. Laura T. Murphy and Nyrola Elimä, *In Broad Daylight: Uyghur Forced Labour and Global Solar Supply Chains* (Sheffield, UK: Helena Kennedy Centre for International Justice, Sheffield Hallam University, 2021), 7, https://www.shu.ac.uk/; and Dave Doody, "Chapter 11: Onboard Systems," *Basics of Space Flight*, National Aeronautics and Space Administration, accessed April 16, 2024, https://science.nasa.gov/.

40. Debamanyu Das, "Role of the State in the Energy Transition: The Case of China and Lessons for the United States," SSRN, October 24, 2023, 21–22, 26–42, http://dx.doi.org/.

41. Pius Ginting and Ellen Moore, "Indonesia Morowali Industrial Park (IMIP)," People's Map of Global China, November 22, 2021, https://thepeoplesmap.net/.

42. "China Export Curbs Choke Off Shipments of Gallium, Germanium for Second Month," Reuters, October 19, 2023, https://www.reuters.com/; Siyi Liu and Dominique Patton, "China, World's Top Graphite Producer, Tightens Exports of Key Battery Material," Reuters, October 20, 2023, https://www.reuters.com/; and "Chinese Exports of Battery Material Graphite Plunge on Controls," Bloomberg, January 21, 2024, https://www.bloomberg.com/.

43. Brian W. Jaskula, "Gallium," in *Mineral Commodity Summaries 2024*, 74, https://pubs.usgs.gov/; Amy C. Tolcin, "Germanium," 80, https://pubs.usgs.gov/; and Andrew A. Stewart, "Graphite (Natural)," 84, https://pubs.usgs.gov/.

factories in Europe.[44] In the extreme case, a US-China conflict would severely disrupt mineral imports from Japan and South Korea, two refining powerhouses on which the United States heavily relies.[45] Hence, mineral import dependence creates supply chain risks to the production of US space assets, especially as the United States seeks to increase its space capabilities.[46]

Mineral import dependence also creates price risks to the US commercial space industry, which has become integral to US military space activities.[47] Import disruptions can restrict mineral availability in the United States, increasing mineral prices. Indeed, US space companies have noted the negative impact of high prices on their operations, such as when China restricted rare earth element exports in the early 2010s.[48]

A US Bureau of Industry and Security survey as early as 2014 found that the second leading issue for US operations related to titanium—a key mineral in space assets—was price volatility, with one titanium-related distributor saying costs can vary by 20 percent.[49] Further illustrating the importance of cost in manufacturing US space assets, SpaceX selected stainless steel instead of carbon fiber for the structural material in the Starship partly due to stainless steel's lower cost.[50]

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44. Paul Wiseman and Mae Anderson, "Attacks on Ships in the Red Sea Are Disrupting Global Trade. Here's How It Could Affect What You Buy," AP, January 28, 2024, https://apnews.com/; and Matthew Beecham, "BriefCASE: Navigating the Red Sea Crisis, an Automotive Industry Perspective," S&P Global, February 15, 2024, https://www.spglobal.com/.

45. *Conflict over Taiwan: Assessing Exposure in Asia* (London: Economist Intelligence Unit, 2023), 1–3, 7, https://www.eiu.com/; Keita F. DeCarlo, "The Mineral Industry of Japan," in *2019 Minerals Yearbook: Japan* (Reston, VA: USGS, December 2023), 13.1, https://pubs.usgs.gov/; Jaewon Chung, "The Mineral Industry of the Republic of Korea," in *2019 Minerals Yearbook: Republic of Korea* (Reston, VA: USGS, June 2023), 15.1, https://pubs.usgs.gov/; and *Mineral Commodities Summaries*, 7.

46. Tucker, "Chinese Space."

47. Micah Maidenberg and Drew FitzGerald, "Musk's SpaceX Forges Tighter Links with US Spy and Military Agencies," *Wall Street Journal*, February 20, 2024, https://www.wsj.com/; Joey Roulette and Marisa Taylor, "Exclusive: Musk's SpaceX Is Building Spy Satellite Network for US Intelligence Agency, Sources Say," Reuters, March 16, 2024, https://www.reuters.com/; Audrey Decker, "Pentagon Eyes Starship, Designed for Mars, for Military Missions Somewhat Closer to Home," Defense One, March 15, 2024, https://www.defenseone.com/; Sandra Erwin, "SpaceX Launches US Missile-Defense Satellites," *SpaceNews*, February 14, 2024, https://spacenews.com/; and Jackie Wattles and Ashley Strickland, "SpaceX Falcon Heavy Launches X-37B Plane, One of the US Military's Most Fascinating Secrets," CNN, December 29, 2023, https://www.cnn.com/.

48. Bureau of Industry and Security (BIS), *US Space Industry 'Deep Dive': A Collaboration between the DOC and the USAF, NASA, and NRO, First Waypoint Preliminary Findings* (Washington, DC: US Department of Commerce, October 2012), 39, https://www.bis.doc.gov/.

49. BIS, *US Strategic Material Supply Chain Assessment: Titanium* (Washington, DC: Commerce Department, 2016), 70, 78, https://www.bis.doc.gov/.

50. Kenneth Chang, "What Is SpaceX's Starship? It's Really a Mars Ship," *New York Times*, March 14, 2024, https://www.nytimes.com/; Mike Wall, "Why Elon Musk Turned to Stainless Steel for SpaceX's Starship Mars Rocket," Space.com, January 13, 2019, https://www.space.com/; Brian Wang, "Estimate of the Cost Savings for SpaceX Stainless Steel Super Heavy Starship," *NextBigFuture.com*, January 28, 2019, https://www.nextbigfuture.com/; and Ryan D'Agostino, "Elon Musk: Why I'm Building the Starship Out of Stainless Steel," *Popular Mechanics*, January 22, 2019, https://www.popularmechanics.com/.

In addition, the lack of alternative mineral suppliers and mineral substitutes exacerbates supply risks for manufacturing US space assets. Military space applications require high-purity minerals from qualified suppliers, and transitioning to and certifying new suppliers can take up to 10 years, according to the Aerospace Industries Association.[51] Substituting limited availability minerals with readily available or cheaper minerals can compromise the effectiveness and safety of the space asset.[52] Given the highly demanding environment of space, such performance declines can render space assets inoperable.[53] In short, finding alternative mineral suppliers would likely cause manufacturing delays, and substituting different minerals would potentially cause performance declines in the space assets.

US Policy Options

To mitigate import disruption risks to the supply chains of US space assets, the US government should adopt the following policies: stockpile minerals vital to US space assets; provide concessional financing for US space companies to sign long-term, fixed-price mineral offtake agreements; and impose environmental and labor tariffs on mineral imports produced in countries that do not adhere to equivalent US E&L standards.

Mineral Stockpiling

First, the US government should stockpile minerals necessary in US space assets to mitigate mineral supply constraints and price volatility. In contrast with other industries like the automotive industry, the US space industry relies on smaller volumes of highly specialized materials.[54] Smaller demand enables easier stockpiling as smaller volumes would need to be acquired and stored. When limited mineral supplies or high mineral prices threaten to disrupt the production of US space assets, the government could sell stockpiled minerals to US space companies at fixed prices. China similarly sells stockpiled minerals to its strategic sectors, like the power sector, when high mineral prices threaten downstream production.[55]

The proposed stockpile would serve both strategic and economic purposes, similar to China's mineral stockpile.[56] While the US government currently employs the National Defense Stockpile, which contains many types of minerals, it is used for strategic—not

51. Aerospace Industries Association, *Securing the US Aerospace and Defense Critical Minerals Supply Chain*, white paper, June 14, 2023, 1–2, https://www.aia-aerospace.org/.

52. Karen L. Jones and Chloe I. Skorupa, *Mine Games: Securing America's Critical Mineral Supply* (El Segundo, CA: Center for Space Policy and Strategy, Aerospace Corporation, January 2024), 3, https://csps.aerospace.org/.

53. Jones and Skorupa, 1.

54. Aerospace Industries Association, "Securing the US Aerospace," 2.

55. Mai Nguyen and Min Zhang, "China to Release Copper, Aluminium and Zinc Reserves to Stabilise Prices," Reuters, June 16, 2021, https://www.reuters.com/; and Andy Home, "Learning to Live with (Talk of) Chinese State Metal Sales: Andy Home," Reuters, June 16, 2021, https://www.reuters.com/.

56. Gregory Wischer, "China Shows How Western Governments Should Stockpile Minerals," Strategist, March 6, 2024, https://www.aspistrategist.org.au/; and Wischer and Bazilian, "Great Mineral Powers."

economic—purposes, intended to reduce supply chain risks to the United States in the event of a national emergency, like a military conflict.[57] The National Defense Stockpile is prohibited from being used as an economic stockpile that sells minerals when prices are high and purchases minerals when prices are low.[58] Therefore, a new mineral stockpile specific to space assets and separate from that reserve should be created.

With the lack of US refining capacity for some minerals, the government would need to stockpile highly refined metal products that US space manufacturers could incorporate into their manufacturing lines without extensive processing. The relatively small mineral demand of individual space companies does allow some companies to undertake smaller batch refining operations. For example, SpaceX, which has its own metallurgy team and foundry, produces its proprietary SX500 alloy for the Raptor rocket engines.[59]

Nonetheless, most US space companies do not have the resources available to SpaceX; thus, the US government should stockpile highly refined metal products that could be integrated into manufacturing lines absent considerable processing. To mitigate the industry's limited access to refining capacity, the government should also consider how it can help companies procure the necessary processing equipment and technology to convert minerals into metals and chemicals for manufacturing space assets.

Concessional Financing

Second, the government should provide concessional financing for US space companies to sign long-term, fixed-price mineral offtake agreements.[60] This means that the mineral producer would agree to sell the space company a certain volume of the minerals at a set price over a specific time frame to attenuate mineral supply constraints and price volatility. US space companies sometimes face limited mineral availability and higher mineral prices due to other industries' larger demand and production cycles. For instance, the 2014 survey on titanium found that industry players expected the increased production of the Boeing 787 aircraft and Airbus A350 aircraft would increase titanium prices and lead times.[61]

57. Cameron M. Keys, *Emergency Access to Strategic and Critical Materials: The National Defense Stockpile*, R47833 (Washington, DC: Congressional Research Service, November 14, 2023) 43–44, https://crsreports.congress.gov/; BIS Request for Public Comments on the Potential Market Impact of the Proposed Fiscal Year 2025 Annual Materials Plan from the National Defense Stockpile Market Impact Committee, 88 Fed. Reg. 170, 60634 (Sept. 5, 2023), https://www.govinfo.gov/; *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth: 100-Day Reviews under Executive Order 14017* (Washington, DC: White House, June 2021), 188, https://www.whitehouse.gov/; and Gregory Wischer and Jack Little, "The US Government Should Stockpile More Critical Minerals," *War on the Rocks,* September 27, 2023, https://warontherocks.com/.

58. Keys, 2; and BIS.

59. Brian Wang, "SpaceX Casting Raptor Engine Parts from Supersteel Alloys," *NextBigFuture*, February 18, 2019, https://www.nextbigfuture.com/.

60. See Wischer and Bazilian, "Great Mineral Powers."

61. BIS, *Titanium*, 85–86.

Likewise, a US space company in 2012 said it faced limited availability of carbon graphite due to competing demand from the production of the A350 and A380 aircraft.[62] In a competitive global market with high mineral demand, long-term offtake agreements at fixed prices could help secure minerals for the US space industry.

To further strengthen US mineral supply chains, government financing of offtake agreements should require borrowing space companies first to source domestically produced minerals if domestic supplies are available and then source foreign-produced minerals from geopolitically aligned countries. Critically, if the offtake agreements are signed with production facilities in East Asia, such as Japan and South Korea, these mineral supplies could be disrupted by US-China military tensions and a US-China conflict; therefore, the US government should condition the financing of offtake agreements with production facilities in East Asia on the desired materials not being produced in other partner countries such as Canada.

Lastly, mineral producers may prefer floating-price contracts over fixed-price contracts because they expect mineral prices to increase over the long term, but these producers also prefer long-term agreements due to guaranteed long-term revenue. Thus, mineral producers should be amenable to long-term, fixed-price mineral offtake agreements.

While the US government has not provided financing to companies to sign offtake agreements with mineral producers, the government has signed offtake agreements directly with mineral producers before. For example, in 1951, the US government contracted with the Calera Mining Company "for the purchase of 6.5 million pounds of cobalt-nickel alloy containing not less than 93 percent cobalt and not more than 7 percent nickel at a fixed premium price," from a mine in Lemhi County, Idaho.[63] Additionally, while uranium is not considered a critical mineral—which is defined as a nonfuel mineral—the US government has also directly procured domestic uranium ore.[64]

Regarding the structure of the proposed policy, one existing program that holds some similarities is financing from the US Export-Import Bank, which provides financing to foreign buyers of US goods. With the proposed policy, the US government would similarly provide financing to US space companies buying critical minerals.

Environmental and Labor Tariffs

Third, the US government should impose E&L tariffs on mineral imports produced in countries that do not adhere to equivalent US environmental and labor standards. Minerals produced in countries with lower standards have lower costs than minerals produced in the United States, which has strict regulations regarding waste management and carbon emissions. Such tariffs would offset this unfair cost advantage and

62. BIS, *Deep Dive*, 39.

63. Joseph H. Bilbrey Jr., *Colbalt: A Materials Survey*, Information Circular 8103 (Washington, DC: US Department of the Interior, Bureau of Mines, 1962), 21–22, https://dggs.alaska.gov/.

64. Michael Scott and Edward M. Heppenstall, "Atomic Energy – Uranium Procurement – Legal Aspects of the AEC Domestic Ore Purchase Program," *Michigan Law Review* 56, no. 5 (1958), https://repository.law.umich.edu/.

incentivize US space companies to source minerals primarily from the United States and secondarily from partner countries, such as Australia.

The government should also ban mineral imports produced in a manner suspected of violating environmental protections and labor rights. For example, the Uyghur Forced Labor Prevention Act already in place seeks to prevent goods made with forced labor in China's Xinjiang region from entering the United States.[65] The US government should seek to do the same for minerals regarding environmental and labor practices in other regions. For instance, it should aim to prevent nickel and cobalt produced in Indonesia's Sulawesi Island and North Maluku from entering the United States due to environmental abuses.[66] Imposing tariffs for environmental and labor reasons has better chances of garnering bipartisan political support. Ultimately, E&L tariffs and import bans should incentivize US space companies to source minerals domestically and from partner countries with high environmental and labor standards.

Conclusion

US space assets are mineral-intensive. Satellites, DA-ASAT weapons, rocket bodies, and other assets all require substantial volumes and various types of minerals. But the supply chains for minerals vital in US space assets face risks of mineral import disruptions such as export controls and interrupted shipping lanes. Such import disruptions can restrict mineral availability and cause price volatility, negatively impacting the production of US space assets. These conditions could prove particularly detrimental to the US military in a conflict with China, which itself is a major supplier of minerals to the United States.

To help mitigate risks to these vital mineral supply chains, the US government with the US Space Force as the primary coordinator should stockpile minerals critical to US space assets; provide concessional financing for US space companies to sign long-term, fixed-price mineral offtake agreements; and impose E&L tariffs on mineral imports produced in countries that do not adhere to equivalent US E&L standards. Such secure access to sufficient mineral volumes is critical for accelerated and uninterrupted production of US space assets and the preservation of US space leadership. **Æ**

65. An Act to Ensure That Goods Made with Forced Labor in the Xinjiang Uyghur Autonomous Region of the People's Republic of China Do Not Enter the United States Market, and for Other Purposes, Pub. L. No. 117-78, 135 Stat. 1525 (2021), https://www.govinfo.gov/.

66. Endang Naryono, "Nickel Mine Exploitation in Indonesia, between a Blessing and a Disaster of Environmental Damage," preprint, OSF Preprints, September 19, 2019, https://doi.org/; and *Nickel Unearthed: The Human and Climate Costs of Indonesia's Nickel Industry* (Berkeley, CA: Climate Rights International, January 2024), https://cri.org/.

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