Managing Risk

MINERAL SUPPLY CHAINS AND SPACE ASSETS

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Mitigating Manufacturing Dependencies

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. 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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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. In fact, the US military has officially declared space a warfighting domain. 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.

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. 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.

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. Further, one 2022 analysis warns, “The People's Liberation Army has the incentives and capabilities to conduct preemptive attacks against US space

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assets," including satellites. As evidenced by its antisatellite test in 2007, China has also shown a willingness to use antisatellite weapons, regardless of the resulting space debris. 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. Metallic materials with high strength-to-weight ratios, such as aluminum, titanium, and stainless steel, help reduce launch costs and increase payload capacity. These minerals must also withstand extreme temperature fluctuations and are often alloyed together, providing additional performance benefits.

**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. 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.

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...

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arrays contribute substantially to satellite mass. These arrays are predominantly composed of silicon, silver, aluminum, glass, germanium, and gallium (fig. 1).\textsuperscript{13}

![Estimated mass composition of satellites based on 2020 study](image)

**Figure 1. Estimated mass composition of satellites based on 2020 study\textsuperscript{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.\textsuperscript{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.\textsuperscript{18} Thus, it is highly dependent on imports of minerals necessary in satellites, exposing these mineral supply chains to disruption and cost risks.


\textsuperscript{16} Schulz and Glassmeier, 11.


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. 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.

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. 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.

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. The SM-3 also uses rhenium for components exposed to high temperatures.

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. Consequently, if the United States increases SM-3 production due to military expansion or
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).

Propulsion tanks are commonly made of AA2219 aluminum alloy; however, SpaceX’s Super Heavy rocket booster consists of 300-series stainless steel. 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. Wiring in rocket bodies is usually copper, while feedlines and other components are generally made of stainless steel, aluminum alloys, and titanium alloys. Lastly, rocket nozzle extensions are often made of C-103 alloy, which consists of niobium, hafnium, and titanium.

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

Figure 2. Estimated mass composition of propulsion tanks and rocket engines based on 2020 study\textsuperscript{31}

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

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33. Gambogi, 205.
34. Chad A. Friedline, “Niobium (Columbium),” in *Mineral Commodities Summaries*, 126.
considerable military capabilities. 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. 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. 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. 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. 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.

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

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factories in Europe. 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. 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.

Mineral import dependence also creates price risks to the US commercial space industry, which has become integral to US military space activities. 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.

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. 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.

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46. Tucker, “Chinese Space.”


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. Substituting limited availability minerals with readily available or cheaper minerals can compromise the effectiveness and safety of the space asset. Given the highly demanding environment of space, such performance declines can render space assets inoperable. 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. 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.

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

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53. Jones and Skorupa, 1.


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economic—purposes, intended to reduce supply chain risks to the United States in the event of a national emergency, like a military conflict. 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. 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.

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. 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.


58. Keys, 2; and BIS.


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

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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. 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. 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. 

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