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Investigation of U.S. Foreign Reliance on Critical Minerals—U.S. Geological Survey Technical Input Document in Response to Executive Order No. 13953 Signed September 30, 2020

Open-File Report 2020–1127
Version 1.1, December 7, 2020

U.S. Department of the Interior
U.S. Geological Survey

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By Nedal T. Nassar, Elisa Alonso, and Jamie L. Brainard

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DAVID BERNHARDT, Secretary

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

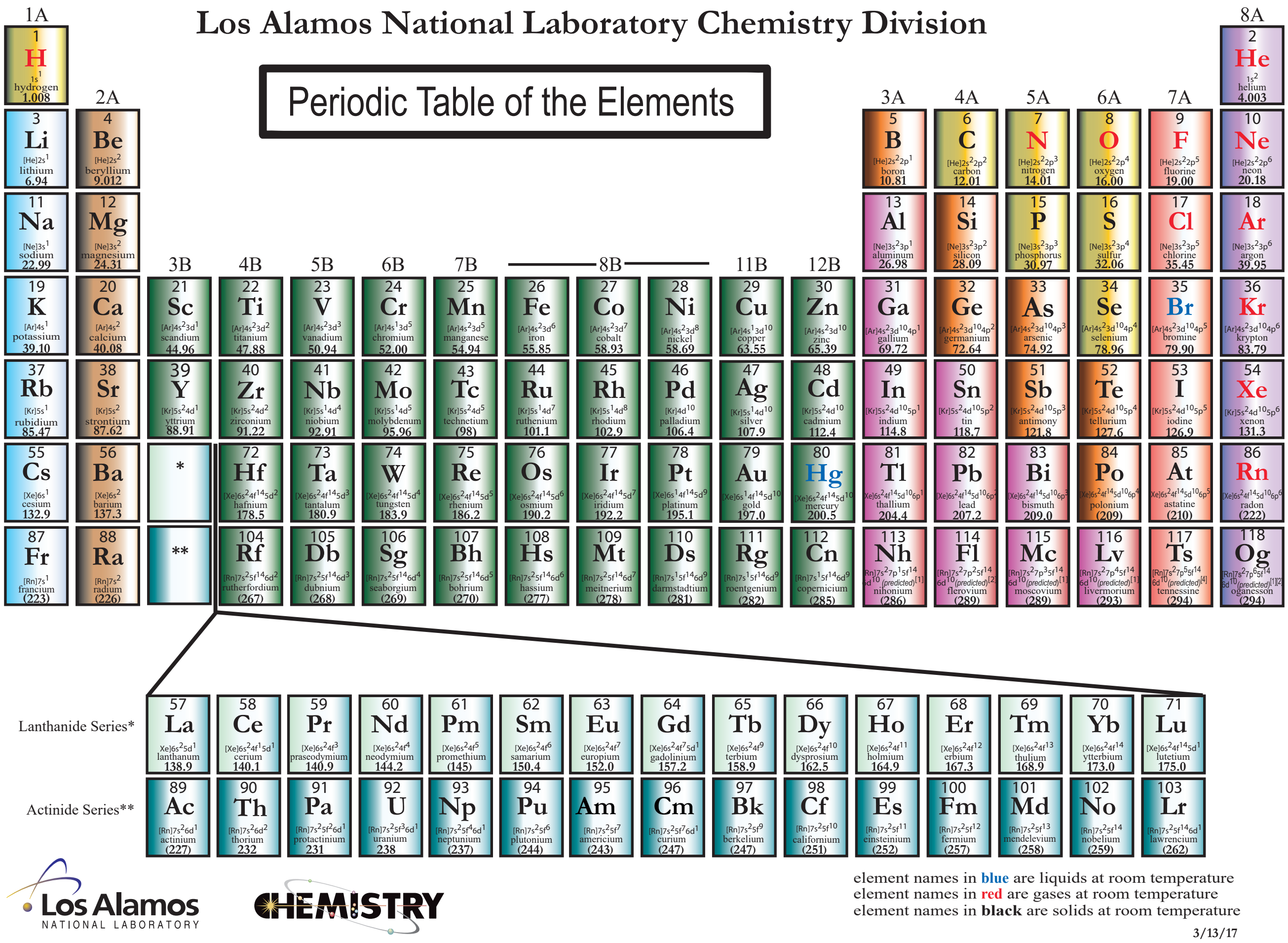
Multiply	By	To obtain
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
ton, long (2,240 lb)	1.016	metric ton (t)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]

Abbreviations

APT	ammonium paratungstate
D.R. Congo	Democratic Republic of the Congo
E.O.	Executive Order
HHI	Hirschman-Herfindahl Index
HTS	Harmonized Tariff Schedule
NdFeB	neodymium-iron-boron permanent magnets
NDS	National Defense Stockpile
NIR	Net import reliance
PGM	platinum-group metal
REE	rare earth element
SEG	samarium, europium, and gadolinium
SEG+	samarium, europium, gadolinium plus a mix of heavy rare earth elements
SmCo	samarium-cobalt permanent magnets
U.S.	United States of America
USGS	U.S. Geological Survey



Modified from Los Alamos National Laboratory Chemistry Division; available at https://periodic.lanl.gov/images/periodictable-3-13-17.pdf

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Abstract

Over the past few decades (1990–2019), the United States has become reliant on foreign sources to meet domestic demand for a large and growing number of mineral commodities. In combination with recent trends towards progressively concentrated supply of mineral commodities from a limited number of countries, this heightened import reliance may increase the risk to the United States economy and national security. Several factors obscure the true net import reliance of mineral commodities essential to the United States, including indirect trade reliance, embedded trade reliance, and foreign ownership. This report provides a detailed overview of contributions to and trends of these mineral commodity supply risks and provides an outline of the salient factors pertaining to each mineral commodity's supply chain. It also describes some additional considerations and provides a general framework for evaluating different strategies aimed at reducing net import reliance and supply risk.

Statement of Issue

Pursuant to the Presidential Executive Order (E.O.) 13953 signed on September 30, 2020, "Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries," the Secretary of the Interior, in consultation with the Secretary of the Treasury, the Secretary of Defense, the Secretary of Commerce, and the heads of other agencies, as appropriate, was tasked with "investigating our Nation's undue reliance on critical minerals, in processed or unprocessed form, from foreign adversaries." This report summarizes the findings of that investigation for over 60 mineral commodities, including those identified by the U.S. Department of the Interior as "critical" to the U.S. economy and national security (Fortier and others, 2018). This report identifies and categorizes the main sources of U.S. mineral commodity imports according to existing security of supply agreements with the United States and the U.S. Department of Commerce's list of nonmarket economies; quantifies the concentration of import sources; identifies net import reliance considerations, trends, and technical options salient for each mineral commodity; highlights factors that may obscure the true net import reliance; and provides a general framework for evaluating strategies that may help reduce U.S. net import reliance. This report is intended to serve as a technical input document that can be used to address Section 1(a) of the Executive Order.

Introduction

From infrastructure and transportation to communication and healthcare, the United States is dependent on the reliable supply of nonfuel mineral commodities critical for its economy and national security. As technology advances, the reliance on critical mineral commodities[1] likely will continue to grow. There are, however, concerns regarding the reliability of supplies for some of these mineral commodities (Graedel and others, 2012; Nassar and others, 2015; Nassar and others, 2020). Disruptions to mineral supply may be caused by a variety of factors, including natural disasters, labor strikes, civil unrest, trade disputes, conflict, government actions, mine accidents, corporate failure, and others (Hatayama and Tahara, 2018; Nassar and others, 2020; Schnebele and others, 2019). The likelihood and impact of any of these types of events causing a major supply disruption is compounded when a substantial portion of global production is concentrated within a single country or small geographic region. Thus, concerns regarding the reliability of supply often stem from the fact that the mining and processing of many mineral commodities

[1]A "critical mineral," as defined by the E.O. 13817, is a mineral (1) identified to be a nonfuel mineral or mineral material essential to the economic and national security of the United States, (2) from a supply chain that is vulnerable to disruption, and (3) that serves an essential function in the manufacturing of a product, the absence of which would have substantial consequences for the U.S. economy or national security.

is highly concentrated in a few countries (Fortier and others, 2018; Nassar and others, 2020). For example, tantalum and cobalt are predominantly mined in the Democratic Republic of the Congo (D.R. Congo), niobium in Brazil, the platinum-group metals (PGMs) in South Africa, and many more mineral commodities in China and other countries (U.S. Geological Survey, 2020a; U.S. Geological Survey, 2020b). Figure 1 illustrates this geopolitical concentration of production by displaying the global production share for a subset of countries in 2018 for various mineral commodities.

Production concentration has increased markedly over the past few decades for many mineral commodities. As noted by Fortier and others (2018), this "trend reflects changes in global demand for materials, comparative advantages in production ([for example,] aluminum production from low-cost energy in United Arab Emirates), or government policies to secure domestic supplies of strategic materials ([for example,] beryllium in the United States)." Perhaps the most notable global shift has been the increasing production of mineral commodities in China. As illustrated in figure 2, China's share of global mineral production and processing has grown markedly since 1990 for many mineral commodities, including aluminum, bismuth, refined cobalt, gallium, lead, magnesite, magnesium metal, mercury, the rare earth elements (REEs), silicon, steel (raw), titanium, vanadium, and zinc.

The increased concentration of production in a limited number of countries (as illustrated in fig. 1 and fig. 2) has been accompanied by an increase in reliance on foreign mineral imports for many industrialized nations, including the United States. The U.S. Geological Survey (USGS) National Minerals Information Center has tracked U.S. net import reliance (NIR) for many decades. NIR is calculated as the quantity of imported materials less exports and changes in government and industry stocks and is expressed as a percentage of domestic consumption (U.S. Geological Survey, 2020b). For example, NIR is 100 percent when the entire consumption of a mineral commodity in the United States is based on foreign sources and there is no domestic production or net adjustments to stocks. In contrast, when U.S. production of a mineral commodity exceeds domestic consumption, the United States is a net exporter, and NIR is zero.

Figure 3 illustrates that the number of mineral commodities for which the United States is at least 25 percent net import reliant has increased from 21 mineral commodities in 1954 to 58 mineral commodities in 2019. This increase in NIR is owing to several factors that are largely similar to those that have led to increased mineral production concentration (that is, comparative advantage and governmental policies).

Importantly, the countries on which the United States is highly reliant vary by commodity. This report summarizes an investigation into those sources. It also describes and discusses some additional factors to consider when examining NIR and provides a general framework for evaluating different strategies aimed at reducing NIR and supply risk overall. Finally, a detailed commodity-by-commodity review of foreign reliance considerations, trends, and options is provided.

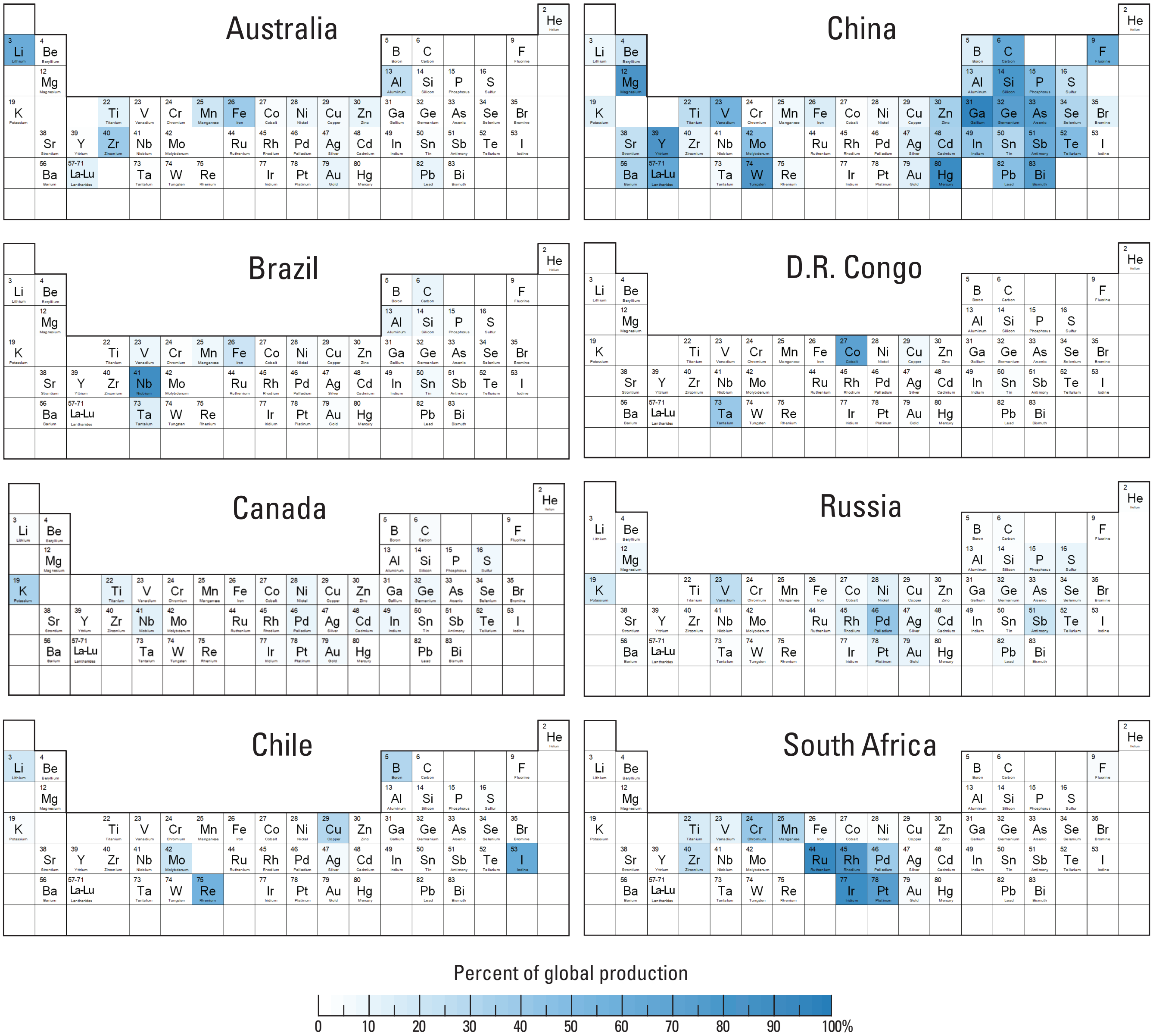

Figure 1. Mineral commodity production concentration. For selected elements of the periodic table (for which the element's name, symbol, and atomic number are displayed), the figure displays the estimated share of each associated mineral commodity's global production in 2018 for various countries, on a white-to-blue color gradient, with darker blue shades indicating a higher percentage of global mine production for that country in that year. Elements not assessed are not labeled. Natural graphite production is noted under carbon ("C"). Magnesium production refers to magnesium metal production. Titanium production refers to titanium mineral concentrate production. Data sources: U.S. Geological Survey (2020a), U.S. Geological Survey (2020b), and other references, methods, and assumptions cited and noted in Nassar and others (2020). Unless otherwise specified here or in these references, production refers to mine or primary production.

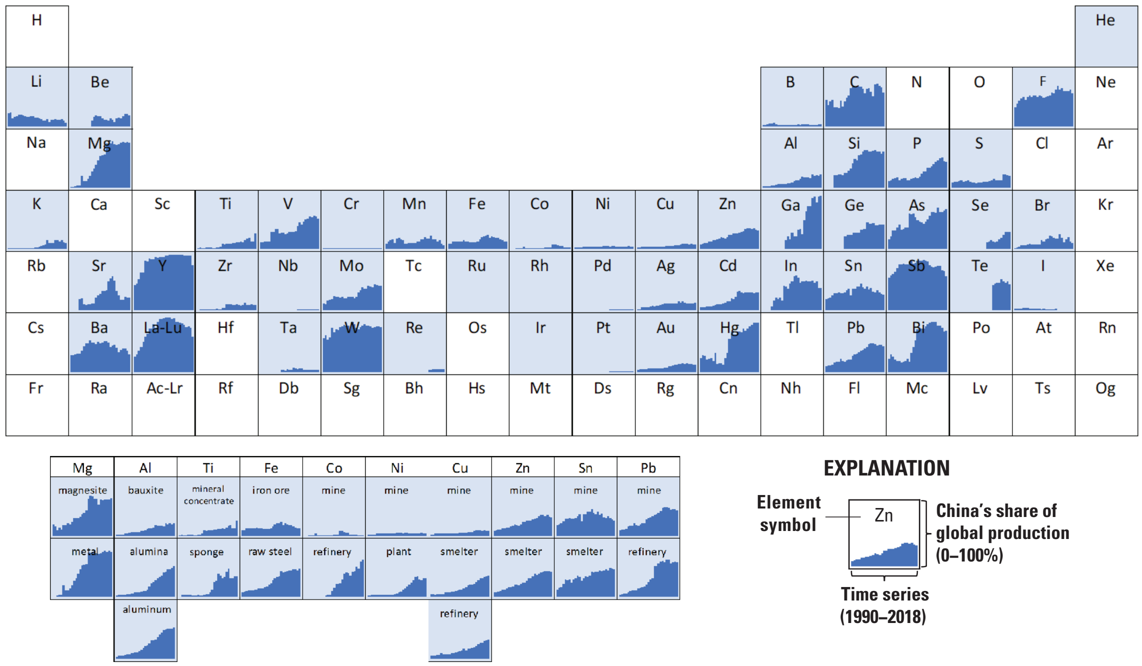

Figure 2. China's share of global primary mineral commodity production over time. For selected elements of the periodic table, the figure displays a time series of China's estimated share of global production for various associated mineral commodities for the years 1990–2018. Data sources: U.S. Geological Survey (2020a), U.S. Geological Survey (2020b), and other references, methods, and assumptions cited and noted in Nassar and others (2020) and U.S. National Science and Technology Council (2016). In the periodic table, production refers to primary production or mine production. In the subfigure below the periodic table, multiple supply chain stages or forms are displayed for each mineral commodity. Elements not assessed are white. For a few mineral commodities (gallium, germanium, indium, selenium, silicon, strontium, and tellurium), data are not available for all years in the time series.

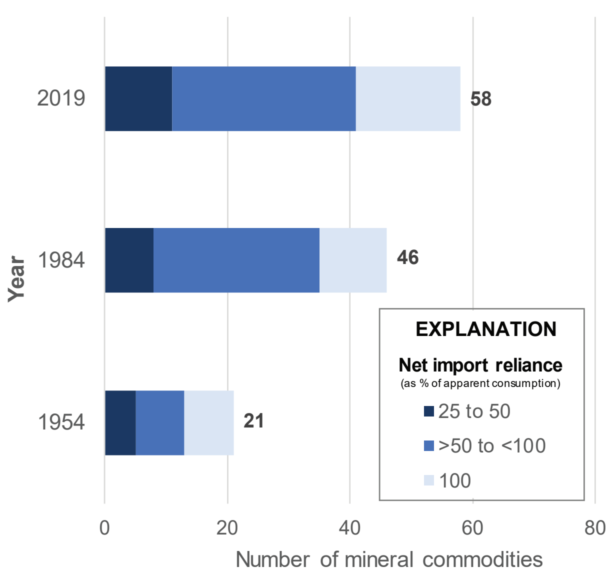

Figure 3. U.S. net import reliance over time. Figure 3 indicates the number of mineral commodities for which the United States is at least 25 percent net import reliant for the years 1954, 1984, and 2019. Data sources: U.S. Geological Survey (2020b) and Fortier and others (2015).

U.S. Mineral Commodity Net Import Reliance

Overview

The United States imports mineral commodities from many countries (U.S. Geological Survey, 2020b). An examination of data collected and analysis conducted by Nassar and others (2020) reveals that the United States imported mineral commodities from more than 100 countries and localities in recent years (2007-2016). Although much of the quantity and value of this trade occurs with a small subset of regional trading partners such as Canada, it is important to examine the sources of supply for mineral commodities individually because examining the total trade quantity and value across mineral commodities may skew the perspective towards large volume commodities (that is, aluminum, copper, and iron ore) and precious metals (that is, gold, silver, and the PGMs).

The sources of various commodities consumed in the United States are displayed in figure 4 for 2018. In this figure, the sources of U.S. mineral commodities are grouped into three categories: domestic sources and partner countries, nonmarket economy countries, and all other countries. In this analysis, "partner countries" includes countries with which the United States has an active security of supply agreement (U.S. Department of Defense, 2020): Australia, Canada, Finland, Italy, The Netherlands, Norway, Spain, Sweden, and the United Kingdom. Other groupings, such as those with which the United States has a collective defense arrangement (U.S. Department of State, 2017) or a free trade agreement (Office of the United States Trade Representative, 2020), are possible but are not presented here.

Nonmarket economy countries are those defined by the U.S. Department of Commerce for purposes of application of the U.S. antidumping and countervailing duty laws (International Trade Administration, 2020): Armenia, Azerbaijan, Belarus, China, Georgia, Kyrgyz Republic, Moldova, Tajikistan, Turkmenistan, Uzbekistan, and Vietnam. Here again, other categorizations are possible.

These country groupings were created on the basis of existing categories and formal international agreements and are not intended to suggest any policy considerations.

Overall, this analysis indicates that the United States obtained materials for much of its consumption of beryllium, boron, helium, gold, molybdenum, potash, zirconium, and other mineral commodities from domestic sources and partner countries. In contrast, a notable portion of the REEs (listed as the lanthanides, "La-Lu," and yttrium, "Y"), bismuth, and to a lesser degree, arsenic, antimony, indium, germanium, gallium, and tantalum that were consumed in the United States were obtained from nonmarket economy countries, predominately China. The remaining sources of mineral commodities consumed were other countries (in the third category), such as fluorspar and strontium from Mexico, rhenium from Chile, and chromium from South Africa.

For some mineral commodities, U.S. imports may be predominately sourced from a single country. For example, most of United States imports of potash were from Canada, and most imports of phosphate were from Peru. Figure 5 displays the degree of concentration of U.S. imports for various mineral commodities using the Hirschman-Herfindahl Index (HHI) at the country level. Here, HHI is measured as the sum of the squares of the individual source country's contribution to the total U.S. imports for each mineral commodity. If all U.S. imports for a mineral commodity were from one country, then the HHI would be 10,000.

The results for 2018, displayed in figure 5, highlight that for a few mineral commodities with a high HHI, such as potash, phosphate rock (indicated as phosphorus), and strontium, U.S. imports were mainly sourced from a single country. In contrast, the imports of other mineral commodities, such as cobalt and tantalum, were sourced from several countries, as indicated by their lower HHI. Note that HHI is commonly used by the U.S. Department of Justice and Federal Trade Commission for the purpose of evaluating corporate mergers and acquisitions (U.S. Department of Justice and Federal Trade Commission, 2010). For that purpose, an HHI between 1,500 and 2,500 is considered "moderately concentrated," whereas an HHI greater than 2,500 is considered "highly concentrated" (U.S. Department of Justice and Federal Trade Commission, 2010). Using these categorizations, in 2018, U.S. imports of most (40 of 46) mineral commodities shown would be considered "moderately concentrated" (9 of 46) or "highly concentrated" (31 of 46). Note that figure 5 displays a metric for the country-level concentration to U.S. imports and not net imports. Consequently, commodities such as helium, iron ore, and molybdenum, for which the United States is a net exporter, an HHI of U.S. imports can still be calculated.

Highly concentrated sources of imports may be attributed to several factors, including comparative advantage and trade policies. Importantly, highly concentrated imports, just as highly concentrated production, is not by itself a cause for concern. For example, having highly concentrated imports from a reliable trade partner may be more favorable than having moderately concentrated imports from several less reliable trade partners countries. Other factors to consider are discussed in the next section.

Factors for Consideration

Several additional factors are important to consider in the analysis of U.S. NIR. Three of these factors are indirect trade reliance, embedded trade reliance, and foreign ownership of mineral assets and operations, each of which is discussed below.

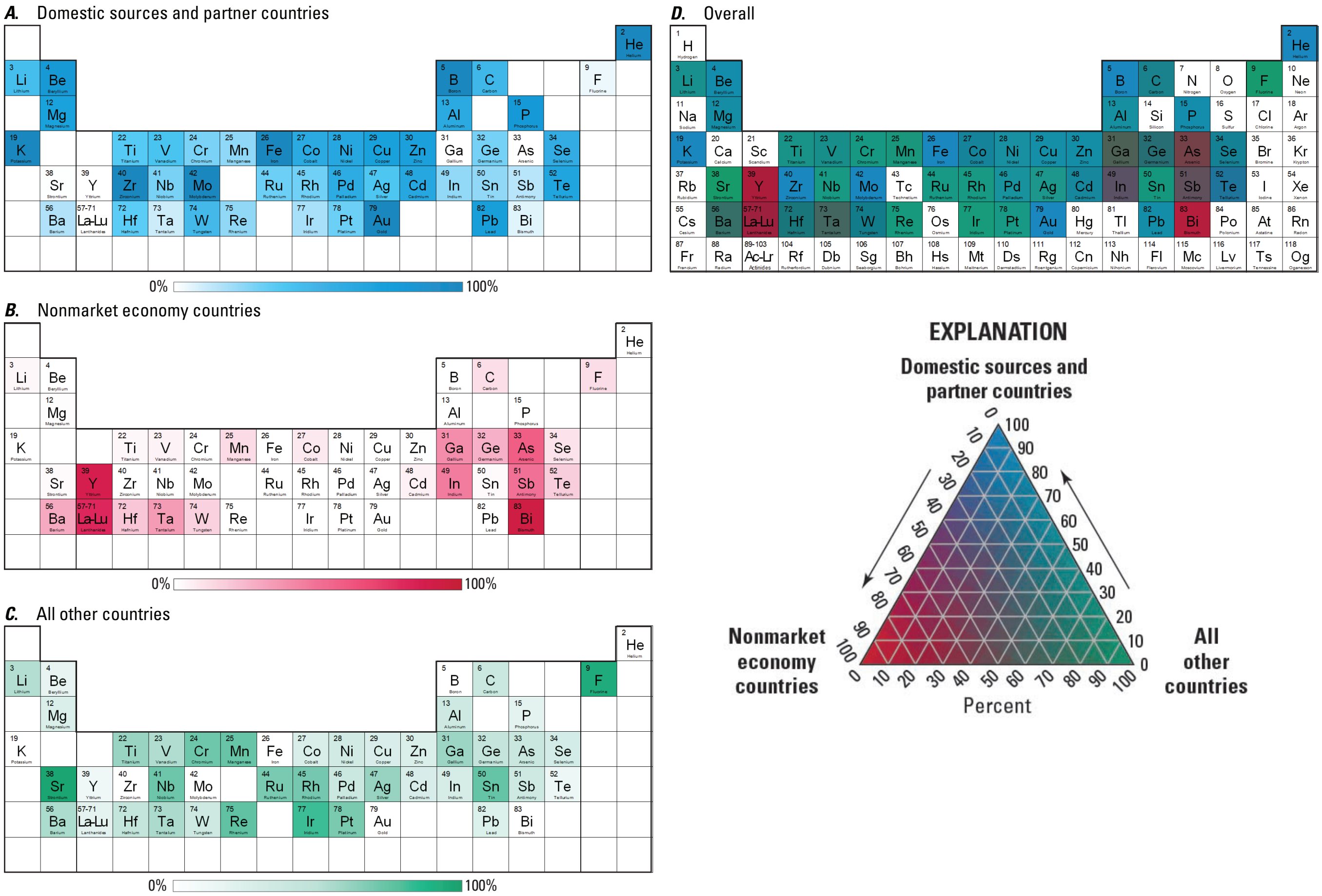

Figure 4. Source of mineral commodities consumed in the United States. For selected elements of the periodic table, the figure displays the estimated percent of 2018 U.S. consumption for the associated mineral commodities obtained from *A*, domestic sources and partner countries, defined here as those having a security of supply agreement with the United States; *B*, nonmarket economy countries as defined by the U.S. Department of Commerce; and *C*, all other countries on a color gradient from white to blue, red, and green, respectively. A ternary diagram, based on the mix of sources from these three categories, is displayed in subfigure *D*, Elements not assessed are not labeled in subfigures *A*–*C* and are not colored in subfigure *D*. Data pertain to refinery or metal production and include secondary production (old scrap recycling), where applicable and available. Estimates are based on methods, assumptions, and references utilized in Nassar and others (2020), updated to 2018, and with the addition of graphite (listed under carbon, "C") includes natural and synthetic graphite consumption with data on synthetic graphite obtained from Roskill Information Services Ltd. (2018); and hafnium and fluorspar with data obtained from Alkane Resources Ltd. (2017) and U.S. Geological Survey (2020a), respectively, along with the associated trade data from the U.S. Census Bureau (2020b).

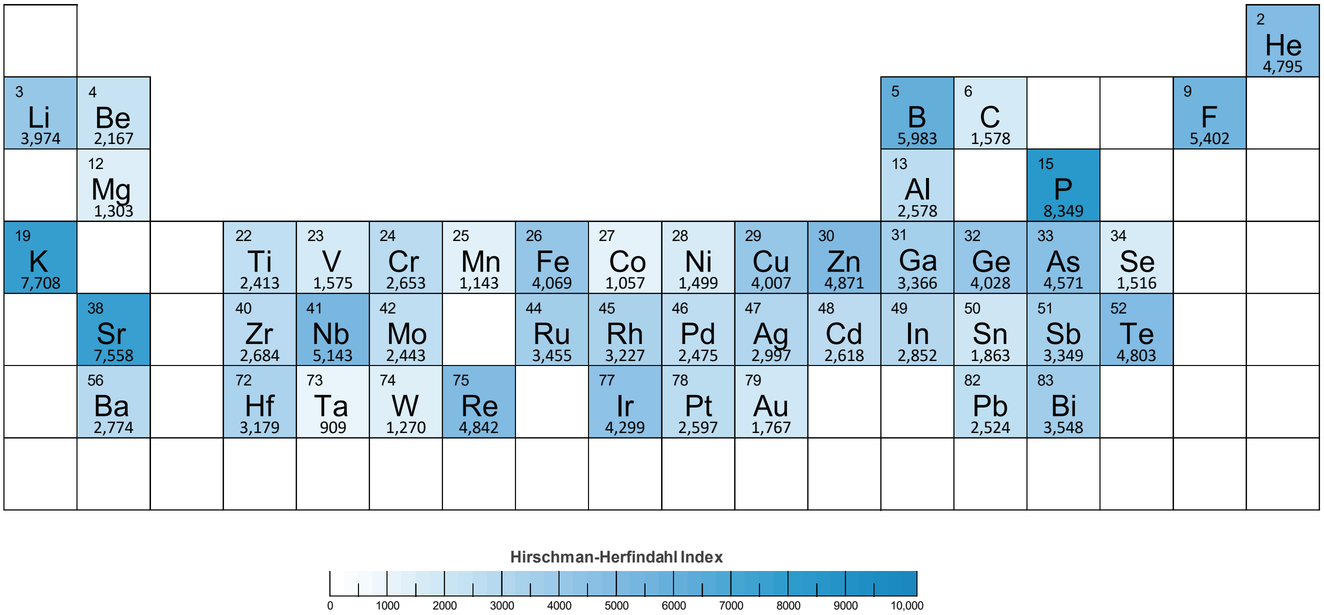

Figure 5. Concentration of U.S. imports of various mineral commodities. For selected elements of the periodic table, the figure displays the estimated concentration of U.S. imports in 2018 for the associated mineral commodities based on the Hirschman-Herfindahl Index (HHI) on a white-to-blue color gradient, with darker blue shades indicating a greater degree of concentration. The HHI of U.S. imports for each mineral commodity is noted below its associated elemental symbol. Results are based on methods, assumptions, and references utilized in Nassar and others (2020), updated to 2018, and with the same additions noted in the caption of figure 4.

Indirect Trade Reliance

Government agencies such as the U.S. Customs and Border Protection and the U.S. Census Bureau capture detailed information on the trade of materials as they cross international borders. Minimal information, however, is available on the path a commodity may have taken from its origin to the United States or any other final destination. The statistics regarding import source countries provided in this report and in other USGS publications that rely on this information typically identify the country of origin where the material was mined or manufactured. However, as noted by the U.S. Census Bureau, "in instances where the country of origin cannot be determined, transactions are credited to the country of shipment" (U.S. Census Bureau, 2020a). In such instances, a commodity might travel through one or more countries under the same Harmonized Tariff Schedule (HTS) code before entering the United States, but the import transaction would be credited only to the country of last shipment. The nature of this indirect trade for various mineral commodity forms is not well understood, and there are multiple reasons for a mineral commodity to be imported and subsequently re-exported. The example trade may be passthroughs, in which a mineral commodity was simply offloaded and then reshipped, or it may have gone through value-added processing without being changed sufficiently to be reclassified under a new HTS code. Regardless of the reason, this example highlights circumstances in which the original source country and, in turn, the true dependency may be obscured.

Additionally, note that when a mineral commodity is significantly altered such that it is classified under a different HTS code, the original source of the mined mineral commodity would not be readily identifiable. For example, the original source of the refined cobalt materials imported from China—although likely to have originated from cobalt mined in the D.R. Congo—cannot be unambiguously known. Ascertaining the original source of the material, as well as any intermediate processing, would require further investigation. The material narratives at the end of this report discuss various forms of each mineral commodity but provide only a preliminary and qualitative understanding of indirect trade reliance.

Embedded Trade Reliance

Another factor that may obscure the true import reliance is that some mineral commodities sourced from a different country are embedded in imported finished and semi-finished goods. Neodymium and other REEs are, for example, imported as permanent magnets as part of hard disk drives and other finished goods. Similarly, mineral commodities originally sourced from other countries can be imported in embedded components of vehicles, televisions, mobile phones, appliances, medical devices, and other goods or may be used to produce finished goods. The embedded content of imports is not accounted for in standard analyses of NIR of mineral commodities, potentially resulting in a significant distortion of the true NIR. Including these embedded flows could highlight the exposure to foreign supply disruptions of manufacturers further down the supply chain or, in the case of finished goods, the final users. Doing so may also identify a different set of source countries for these embedded imports than for raw material imports.

Few studies examine embedded trade reliance. Johnson and Graedel (2008), for example, examined the "end user net import reliance" of the United States by including the NIR for the metal contained in ores, concentrates, refined forms, semi-manufactured goods, and finished goods for five mineral commodities (chromium, copper, lead, silver, and zinc). Johnson and Graedel (2008) found that the end user NIR was higher than the NIR of the raw material forms (ores, concentrates, and refined forms). This is likely to be the case for most mineral commodities and may be especially profound for mineral commodities utilized in goods for which U.S. manufacturers are not major producers but are purchased in large quantities by U.S. consumers (for example, indium-tin-oxide as a transparent conductive coating in flat panel displays).

In its biannual "Requirements Report to the U.S. Congress," the U.S. Defense Logistics Agency has begun to examine the issue of embedded import reliance of the United States for several commodities, including the REEs (U.S. Department of Defense, 2019). Further investigation beyond the scope of this report could determine the extent to which embedded import reliance exposes the U.S. economy and national security to foreign mineral commodity supply disruptions.

Foreign Ownership of Mineral Assets and Operations

A third factor to consider when addressing U.S. NIR is that of foreign ownership of mineral assets and operations. There are instances where the mineral deposit or mining and mineral processing operation of a commodity is partially or completely owned and (or) controlled by foreign companies with strong ties to their governments. For example, Chinese firms have purchased equity stake in lithium deposits and operations in Australia and Chile, niobium operations in Brazil, a rare earth deposit in Greenland, and cobalt operations in the D.R. Congo, Papua New Guinea, and Zambia (S&P Global Market Intelligence, 2020). Investigating China's investment in cobalt assets worldwide, Gulley and others (2019) found that when taking into account Chinese companies' ownership in foreign assets on an equity-share basis, China's share of global cobalt production increases from 2 to 14 percent for cobalt mine materials and from 11 to 33 percent for cobalt intermediate materials (figure 6). Furthermore, if the Chinese companies' equity shares of the production from these assets are assumed to be as secure as its domestic production, then these acquisitions have the effect of reducing China's NIR from 97 percent to an adjusted 68 percent, thereby reducing China's exposure to supply disruptions (Gulley and others, 2019).

Chinese firms are not the only ones to target foreign mineral assets. There are many foreign mineral assets owned and (or) operated by American, Australian, British, Canadian, Japanese, Korean, and Swiss companies with headquarters in other countries (S&P Global Market Intelligence, 2020). The targeting of cobalt, lithium, and niobium assets and operations by Chinese firms may, however, reduce China's exposure to foreign supply disruptions given that these three mineral commodities are among the few for which China does not have adequate domestic supplies to satisfy domestic consumption. They happen to be commodities for which the United States also does not have sufficient domestic supplies.

The set of mineral commodities for which China and the United States might both be exposed to potential supply disruptions was highlighted in a 2018 study (Gulley and others, 2018) in which China's NIR was compared with that of the United States in a four-quadrant matrix (fig. 7). In figure 7, molybdenum falls in the bottom-left corner of quadrant 1 because the United States and China are net exporters of molybdenum. The REEs, indium, tellurium, cobalt refined materials (denoted with a subscript "r") and several other mineral commodities fall within quadrant 2, indicating that the United States is highly import reliant for these mineral commodities, but China is not. In contrast, beryllium, selenium, and a few other mineral commodities fall under quadrant 3, indicating that China does not have sufficient supplies to satisfy domestic consumption of these mineral commodities, but that the United States does. Note that for some mineral commodities this designation might apply because the United States does not consume that material directly. In quadrant 4 are mineral commodities for which the United States and China are more than 50-percent net import reliant. Mineral commodities that fall under this category are thus those for which neither the United States nor China have sufficient domestic supplies to satisfy even one-half of their respective domestic consumption. This concurring dependency may, in turn, lead to global competition as countries attempt to secure supplies of these mineral commodities for their own manufacturing sectors.

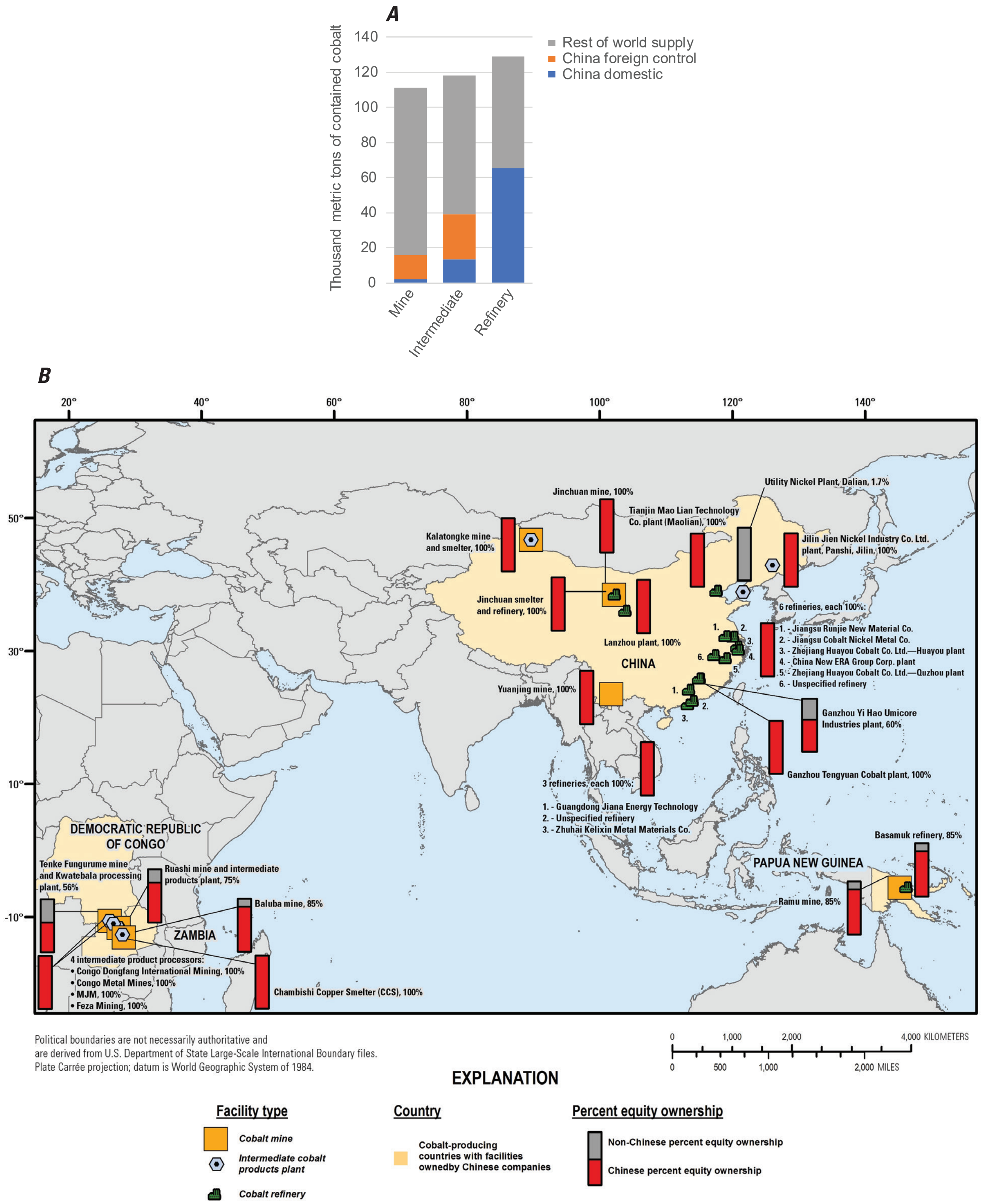

Figure 6. China's global cobalt footprint. *A*, Cobalt mine, intermediate, and refinery production or capacity by China's domestic operations, equity-based share of Chinese firms overseas, and rest of world for 2016. *B*, Map identifies cobalt operations in China and those with some portion of Chinese equity ownership. Based on Gulley and others (2019); map by M. Baker (U.S. Geological Survey, written commun., 2017).

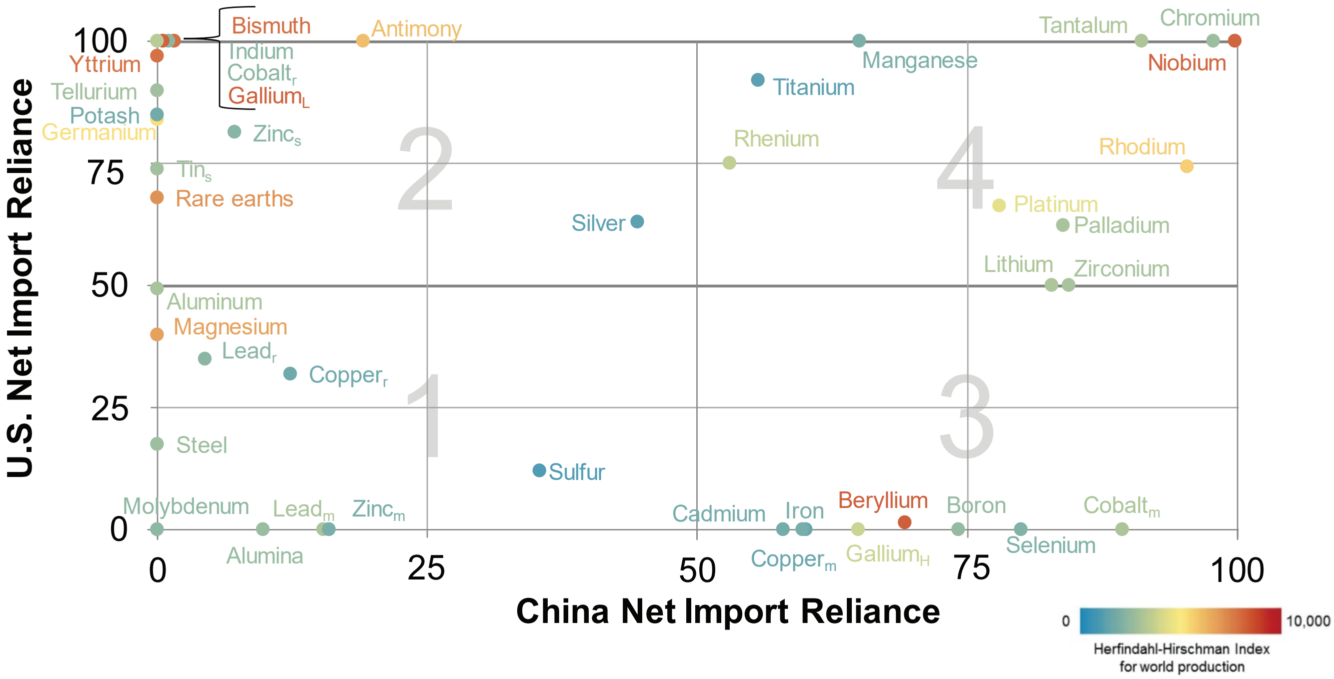

Figure 7. Comparison of net import reliance of the United States and China. The figure displays the net import reliance of the United States (vertical axis) and China (horizontal axis) for 42 mineral commodities for 2014. The color gradient is based on country-level production concentration as measured by the Herfindahl-Hirschman Index (HHI), which is calculated here as the sum of the squares of each producing country's global production share of a given commodity on a 0 to 10,000-point scale. From Gulley and others (2018).

Additional Risk Considerations

The changing nature of mineral supply chains introduces two additional considerations discussed below. The first is that, although there may currently be domestic production, future domestic capability is not guaranteed and deserves ongoing monitoring. The second is that NIR and concentration of supply are risk factors, which when complemented with assessments of economic vulnerability and supply disruption potential may provide a more complete picture of mineral commodity supply risks.

Fragile Domestic Mineral Supply Chains

In standard analyses of NIR, mineral commodities for which the United States is a net exporter are given an NIR of zero. However, the United States as a net exporter of a mineral commodity is not necessarily resilient to the mineral commodity's supply chain disruptions. In some cases, the United States may be an exporter or near net exporter, but there may be only one or two domestic producers (for example, boron, beryllium, cadmium, and selenium). If changes in market conditions or other factors make it difficult for these producers to continue to operate, then the United States may become completely net import reliant for those mineral commodities.

For some mineral commodities domestic mineral production has been decreasing such that the United States is no longer, or will soon no longer be, a net exporter. For example, the United States was a net exporter of alumina until 2016. With declining domestic production over the past few years, the United States imports (as of 2019) more than one-half of its annual alumina consumption (U.S. Geological Survey, 2020b).

Another important factor to consider is that of downstream processing. The United States may be a net exporter of a mineral commodity in the form of ores and concentrates but, owing to the lack of downstream processing capability, may still be a net importer of the refined or final form of that mineral commodity. This is the case for the REEs, zinc, and zirconium (U.S. Geological Survey, 2020b). As such, it is important to examine the entire supply chain of a mineral commodity to determine which forms and processing steps may be the most exposed or susceptible to supply disruptions.

Exposure as a Component of Risk

As described by Nassar and others (2020), NIR is a necessary, but alone an insufficient, condition for supply risk. This is because, in a conventional risk modeling framework, NIR would be considered as the "exposure" component of the risk triangle, with the other two components being "hazard" and “vulnerability” (Crichton, 1999). Consider the results of the supply risk analysis by Nassar and others (2020) for 2016, which are displayed for each risk component on a common 0-1 scale (with higher values indicating a greater potential for risk) in figure 8. In that analysis, silver was considered to have a relatively low supply risk even though the Trade Exposure component (as measured by the U.S. NIR) for silver was relatively high (hovering near 0.7 over the past five years), and the Economic Vulnerability component (as measured by the sum of expenditures on a mineral commodity by each consuming U.S. manufacturing industry relative to the industry’s operating profits, weighted by each industry’s contribution to U.S. gross domestic product) was also determined to be relatively high at approximately 0.8. The overall risk was deemed to be low (at approximately 0.2) because the Disruption Potential component (as measured by the country-level concentration production outside the United States, weighted by each country’s ability and willingness to supply to the United States) was deemed to be very low (at approximately 0.02) owing to the large number of silver producers globally. In contrast, for mineral commodities like neodymium, for which all three risk components were deemed to be moderate to high, the overall supply risk was determined to be relatively high (at greater than 0.6).

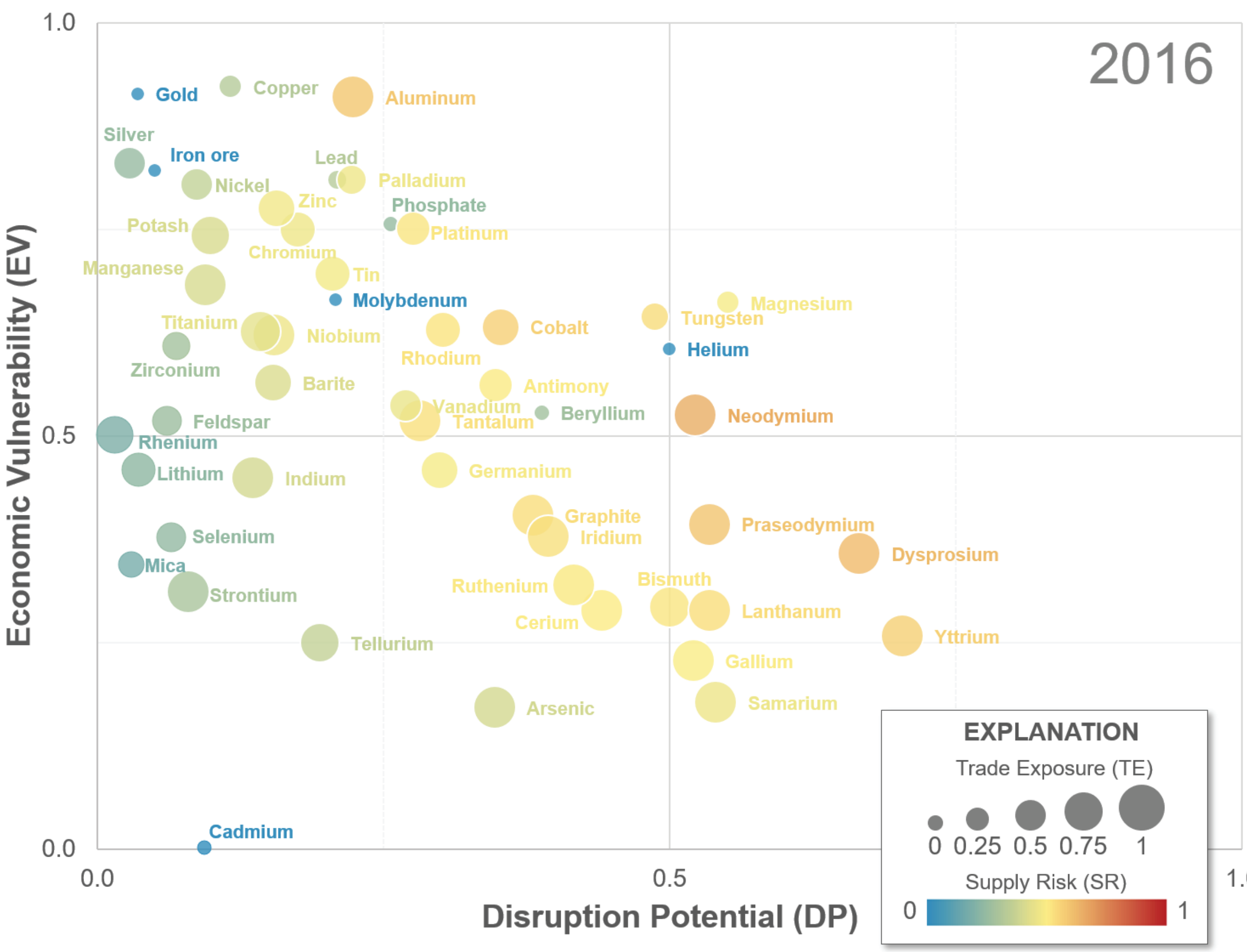

Figure 8. Assessment of mineral commodity supply risk. Disruption Potential (horizontal axis), Economic Vulnerability (vertical axis), Trade Exposure (point size), and overall Supply Risk (point shade) of the U.S. manufacturing sector for various mineral commodities in 2016. From Nassar and others (2020).

Strategies for Reducing Net Import Reliance

Various strategies can be implemented to reduce the NIR of the United States (or any other country), many of which may require (or result in) the improvement of the comparative advantage of domestic mineral supply chains. These strategies include increasing domestic primary and secondary (that is, recycling) production; diversifying and reinforcing global supply chains to eliminate single points of failure and bottlenecks; securing supplies with reliable partners through off-take agreements and stronger trade ties; developing alternative materials that have lower supply risk and supply chains that are largely independent from those of the mineral commodity in question; maintaining strategic inventories; utilizing less of the mineral commodity through material thrifting; and employing enhanced manufacturing techniques, such as additive manufacturing (that is, 3D printing) and near-net shape forging processes that can reduce the amount of waste generated and thus the amount of mineral commodity needed. These and other initiatives are identified as "calls to action" as part of the Federal strategy entitled "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals" (U.S. Department of Commerce, 2019) that is currently (2020) being implemented by various U.S. Federal Government agencies and coordinated through the U.S. National Science & Technology Council's Critical Minerals Subcommittee.

These strategies may be means of reducing NIR with the goal of reducing the risk of supply chain disruption. How effective each of these strategies is at reducing NIR will vary by mineral commodity. Moreover, each of these strategies has strengths but also significant limitations. For example, the ability of viable substitutes to reduce NIR (and the overall supply risk) may be limited by supply constraints of the substitute material (Binnemans and others, 2018; Graedel and others, 2012; Nassar, 2015). This may occur because mineral commodities that are good substitutes are those with similar chemical and physical properties and are thus typically found in the same ore deposits (Nassar, 2015). For example, in certain applications, the coproduced PGMs can often substitute for one another and for the nickel with which they are sometimes produced as a byproduct (Nassar, 2015). Similarly, the coproduced REEs can substitute for each other in certain applications, as can tellurium and selenium; cobalt and nickel; and tantalum and niobium. The substitution of coproduced mineral commodities may create (or exacerbate existing) supply and demand mismatches if the demand for one of the coproduced mineral commodities requires the overproduction of the other as a result of their relative proportions in the source ore deposits (Nassar, 2015). For example, meeting the future demand for dysprosium may result in the co-production of cerium and other REEs in excess of their projected demand (Elshkaki and Graedel, 2014).

Other NIR reducing strategies have their own unique challenges (for example, low collection rates impede post-consumer recycling, and lack of geologic knowledge hinders mineral asset development). If a specific NIR goal is established, then scenarios can be developed to determine how much each of these strategies can contribute (given their limitations) toward that goal under various assumptions of future domestic demand. Figure 9 provides an illustrative example of how this may be accomplished. Business-as-usual or other scenarios could be created to determine the overall demand for the United States for the mineral commodity in question over a specific time period in the future. Various domestic demand reducing and supply increasing strategies could then be examined to determine how much and how quickly these strategies would contribute towards a reduction in the overall NIR. Because each mineral commodity's supply chain is unique, the most effective strategies will vary by mineral commodity. When the target NIR is achieved, industry and U.S. Government strategic inventories could be maintained at a commensurate level to provide the necessary buffer in the event of a supply disruption.

Note that the target NIR can be objectively determined using a cost-benefit analysis that would compare the direct and indirect costs of each of the strategies to the benefit of reducing the impact of potential supply disruptions. The economic impact of supply disruptions can be used as a proxy for that benefit and would be determined by examining how such disruptions impact the economy.

One of the major challenges in evaluating strategies for reducing NIR is that each mineral commodity supply chain is unique and complex. What applies to one supply chain may not apply to another, and each supply chain produces and uses many mineral forms across many countries. Moreover, over time, supply chains change, whether through depletion of current mines, discovery of new resources and extraction techniques, demand for materials in new technologies, or as a result of changes in material usage in current mining and manufacturing technologies. Supply chains are not only dependent on technical variables, but also are heavily dependent on global market forces. Over time, costs and the supply-demand balance vary, resulting in mines and plants either starting up, expanding, idling, or closing. Therefore, market actions or policy solutions aimed at achieving specific goals may be more complex than is suggested in the illustrative example presented in figure 9.

Furthermore, some actions may have some unforeseen or unintended consequences. In addition to the previously discussed example of substituting a coproduced mineral commodity, instances may occur where the substitute material has (or as a result develops) its own supply chain concerns. In such instances, this action may have an overall negative effect on reducing supply risk. A historical example of this relating to the development of rare earth permanent magnets is provided in Box 1. Another example of unintended consequences relates to thrifting—the use of less of a mineral commodity. Although thrifting may decrease demand for a mineral commodity, it may also make end-of-life recycling less economical because less of the material is available to recycle. An investigation into each of these strategies can reveal their potential effectiveness and highlight unintended consequences.

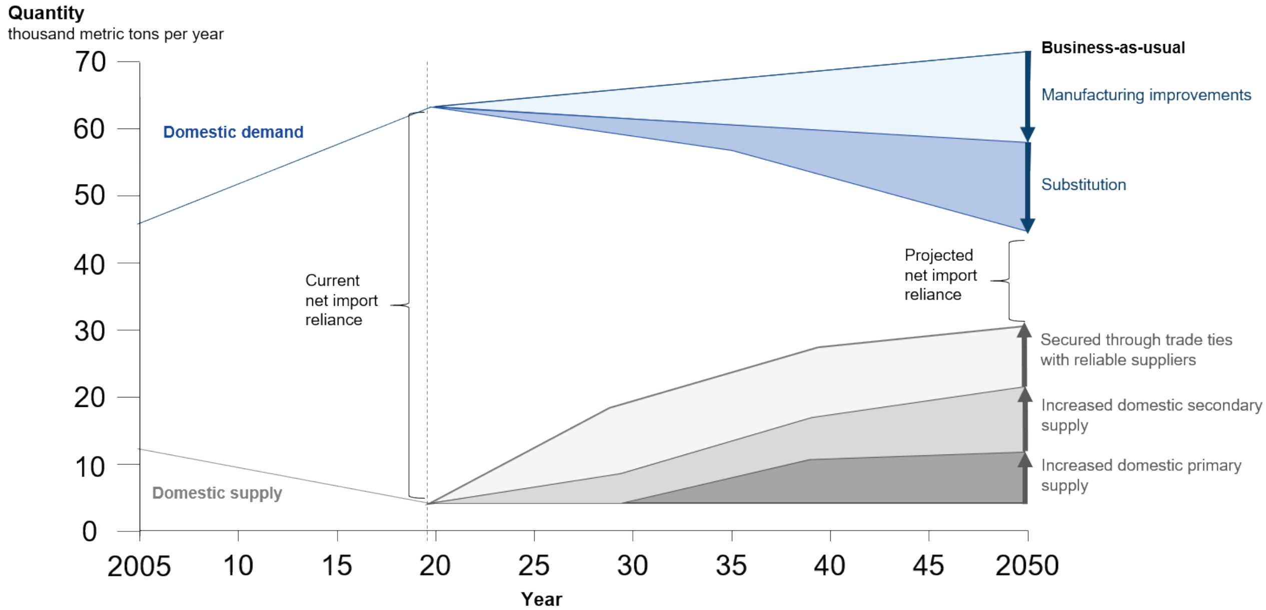

Figure 9. Scenario analysis as a tool for evaluating the potential of different strategies to reduce net import reliance. This is an illustrative example of how net import reliance may be decreased over time by examining the potential contribution of demand reduction strategies (in blue shades) and supply increase strategies (in grey shades).

Box 1. Historical example of substituting rare earths for cobalt

In the 1970s, samarium-cobalt (SmCo) permanent magnets were developed. Despite their superior performance compared to other permanent magnets available at the time, the uptake by industry was relatively slow. Among the concerns at the time was the stability of supply of cobalt from the country then known as Zaire (and now known as the D.R. Congo) (Alonso and others, 2007). These concerns were realized in 1977 and 1978 when insurgents based in neighboring Angola invaded the Shaba (or Katanga) region and occupied an important mining town (Kolwezi) (Cowell, 1981). This led to a panic in the cobalt market such that the price for cobalt increased from $8.8 per kilogram in 1975 to just under $12 per kilogram in late 1977, to $55 per kilogram in early 1979, with dealer spot prices rising to as high as $99 per kilogram (Alonso and others, 2007). In 1983, engineers at General Motors Co. (and independently at Sumitomo Special Metals Co., Ltd. in Japan) developed an alternative to SmCo permanent magnets: neodymium-iron-boron (NdFeB) permanent magnets. These permanent magnets had several advantages over SmCo and avoided the use of cobalt. Adoption by industry was relatively quick.

In 1986, wanting to focus on its core competencies, General Motors Co. formed a subsidiary (Magnequench) to produce NdFeB magnets. In 1995, an investment group purchased this subsidiary. Unknown at the time, the investment group was backed by Chinese companies with close ties to the Chinese government (Mancheri and others, 2013). The Committee on Foreign Investment in the United States approved the sale of the subsidiary under the condition that the manufacturing facility would remain in the United States for a period of time. However, after that time period expired, the company closed its U.S. manufacturing facilities and consolidated its operations in China (Mancheri and others, 2013).

During that time (2002), the sole U.S. producer of rare earths halted its operations at the Mountain Pass Mine (Mancheri and others, 2013). Chinese rare earth production was, however, ramping up and would soon become the world’s largest. In 2010, an incident between a Chinese fishing boat and Japanese coastal patrol resulted in threats from China to cut off rare earth supplies to global markets (Mancheri and others, 2013). These threats have once again increased attention and the desire to find substitute materials for rare earth permanent magnets. Additionally, with advancements in electric vehicles, there is new interest in reducing or eliminating the use of cobalt in lithium-ion batteries owing, in part, to its predominant supply from the D.R. Congo.

Mineral Commodity Overview

Foreign reliance considerations, trends observed in the past decade or so (2005–2019), and technical options for addressing supply concerns for each mineral commodity are summarized in the table 1; more detailed discussion is provided in Appendix 1. The forms in which a given mineral commodity may occur are generally classified as follows: unprocessed forms, including those produced from mining and concentrating operations (for example, ores, concentrates, and crude products), and processed materials, including those that have gone through separation and smelting processes (for example, matte, pig iron, low purity compounds such as oxides, carbonates, sulphates, and ferroalloys), refining and purification processes (for example, metal sponge, powders, and unwrought forms, as well as refined compounds and high-purity products), and metallurgical processes and forms such as ingots, alloys, and wafers.

Table 1. Summary of some of the forms that are produced and traded for each mineral commodity, foreign reliance considerations, trends for the global supply chain, and technical options for the domestic supply chain. Mineral commodities listed include ones with high foreign reliance at some stage in the supply chain. Ores and concentrates are not listed in most cases under the Forms heading but are assumed to be included for all minerals. Data sources include Nassar and others (2020, U.S. Geological Survey (2020a), U.S. Geological Survey (2020b).

Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Alumina and bauxite (nonmetallurgical)	Refractory grade, chemical grade, fused crude alumina, corundum	There is minimal domestic production of nonmetallurgical grades of bauxite and alumina.	Global production of bauxite and alumina have increased over the past decade, with Chinese production accounting for a significant part of the growth. U.S. imports have fluctuated, and production dropped significantly in the past few years.	Many forms and grades of alumina and bauxite exist, and data distinguishing them are lacking. Additional data would make it possible to better tailor options for addressing supply risks.
Aluminum	Metallurgical bauxite, metallurgical alumina, metal, alloys	The domestic supply chain for aluminum production is entirely import reliant for bauxite, which are largely sourced from Jamaica, Brazil, and Guinea. Import reliance is high for both alumina (Brazil and Jamaica) and aluminum (Canada).	U.S. production of aluminum from primary sources has declined over the past decade, whereas production in China has increased.	There is domestic production of metallurgical grade alumina and of both primary and secondary aluminum. Recycled sources of aluminum have provided a steady supply over the past decade. Imports can be sourced from many countries.
Antimony	Oxide, sulfide, metal	There is no domestic mine for antimony, and the single antimony metal producer relies on imports of feedstock containing antimony. China is the largest producer of mined and refined antimony and a major source of imports for the United States.	Global production of antimony has been relatively stable over the past decade, with China, the world's leading producer, losing market share with Russia, the world's second-ranked producer, increasing global market share.	Domestic recycling of scrap offsets some of the import reliance on China. A domestic mine previously extracted resources of antimony ore, stibnite, but it is now on care-and-maintenance status.
Arsenic	Trioxide, metal, arsenic acids, gallium arsenide wafers	The United States is entirely import dependent. For arsenic trioxide, China and Morocco are the main import sources. For metal and gallium arsenide wafers, China is the main import source.	The United States has not produced arsenic trioxide or metal for decades. Global production has been decreasing owing to decreasing demand, in particular, for wood treatment.	Although it is not economically recoverable in the United States, arsenic occurs in ores mined domestically. Recycling of manufacturing scrap of gallium arsenide wafers can supply some quantity of arsenic.
Barite	Mineral, powders	Domestic production occurs at a few mines, which is only a small fraction of apparent consumption. The United States imports largely from China, and from India, Morocco, and Mexico.	Barite demand varies, largely based on the oil and gas industry demand as its largest end use is as a drilling fluid filler material for drilling wells. U.S. production has been variable.	The United States is among more than two dozen countries that produce barite. Some substitution is possible, although not generally pursued at this time.

Table 1. Summary of some of the forms that are produced and traded for each mineral commodity, foreign reliance considerations, trends for the global supply chain, and technical options for the domestic supply chain. Mineral commodities listed include ones with high foreign reliance at some stage in the supply chain. Ores and concentrates are not listed in most cases under the Forms heading but are assumed to be included for all minerals. Data sources include Nassar and others (2020, U.S. Geological Survey (2020a), U.S. Geological Survey (2020b).—Continued

Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Beryllium	Beryl, oxide, metal, beryllium copper master alloy	The United States is the world's leading producer of beryllium and a net exporter. However, only a single company mines and processes beryllium domestically. Few other countries produce beryllium.	U.S. production of beryllium has been somewhat consistent over the past decade. Chinese production has doubled.	Beryllium is crucial to defense applications and cannot be substituted in those applications. There has been legislative action to ensure domestic supply of beryllium and it is held in the National Defense Stockpile (NDS).
Bismuth	Nitrates, carbonates and other compounds, metal	Bismuth is neither mined nor processed in the United States and is mostly imported from China, the world's leading producer.	China has consistently produced more than half of the world's processed bismuth and been the largest import source for the domestic supply chain.	Domestic recycling of bismuth currently accounts for less than 10 percent of the domestic consumption. Bismuth is contained in lead ores mined domestically but processed outside the United States.
Boron	Borates, boric acid, boron, carbide	The United States is a net exporter of boron compounds, with production by two companies accounting for all the domestic mine production.	The United States continues to be one of the world's leading producers of boron compounds. Several other countries also produce boron, but some countries have stopped producing or publishing production data in the past few years.	Domestic mining of boron compounds is used in the domestic supply chain to produce glass, ceramics, cleaning products, abrasives and other products where substitution is possible. Reserves are among the largest globally.
Cadmium	Sulfide, metal	Two domestic companies provide about one half of the supply for meeting apparent consumption. Imports are distributed over a few countries, of which China, Australia, and Canada are most important.	Less than 10 years ago, the United States was a net exporter of cadmium. It is now a net importer.	Cadmium is produced domestically as a byproduct from zinc smelting of zinc ores mined domestically. It is also recycled domestically. Quantitative estimates of reserve are not available.
Cerium	Mischmetal, cerium oxide, carbonate and other compounds, metal	Cerium is mined and concentrated domestically, but as with other rare earth elements (REEs), cerium compounds are produced largely outside the domestic supply chain. Catalyst compounds and polishing powders containing cerium are produced domestically.	China's global market share of mined rare earth compounds has decreased in the past 5 years but is still more than 50 percent. U.S. cerium oxide production has occurred sporadically within the past decade.	Exploration, research, and other actions are currently being taken to address the supply risks for REEs.
Cesium	Oxide, metal, formate and other chemicals	Cesium is not produced domestically. There are no trade data or global production data for cesium.	Trends are difficult to establish in this very small and opaque market.	There is almost no data on cesium and no domestic reserves. Obtaining better data would the first step to evaluating options.
Chromium	Chromite, oxide, sulfate, metal, ferrochromium, high-purity chromium	The U.S. imports chromite ore and ferrochromium largely from South Africa. Chrome metal is largely imported from Russia. These forms of chromium are not produced domestically.	Chromium production in the United States has not occurred in decades. Chromium demand varies on the basis of demand for alloys, especially stainless steels and superalloys.	Recycling of steel containing chromium satisfies a fraction of the domestic chromium demand.

Table 1. Summary of some of the forms that are produced and traded for each mineral commodity, foreign reliance considerations, trends for the global supply chain, and technical options for the domestic supply chain. Mineral commodities listed include ones with high foreign reliance at some stage in the supply chain. Ores and concentrates are not listed in most cases under the Forms heading but are assumed to be included for all minerals. Data sources include Nassar and others (2020, U.S. Geological Survey (2020a), U.S. Geological Survey (2020b).—Continued

Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Cobalt	Chlorides, carbonates, oxides, metal	Most production and all refining occur outside the United States. The United States relies on a variety of countries for consumption needs.	The D.R. Congo continues to be the largest global source of mined cobalt, and China dominates refinery production.	Domestic reserves and resources are limited, but some byproduct production takes place. Recycling of scrap is a significant portion of consumption. Exploration, research, and other actions are currently being taken to address the supply risks.
Copper	Metal, alloys	Copper is a major industrial metal that is produced in many countries, including the United States. Domestic import reliance is low.	Global production has been increasing, and copper demand and supply are tied to economic development and growth. U.S. mine, smelter, and refinery production has been consistent. China has increased refinery production over the past decade to become the world's top producer of refined copper.	The United States mines, smelts, refines, and recycles copper and has significant reserves.
Dysprosium	Heavy REE mix, oxide, metal	Only small amounts of dysprosium are contained in ores mined in the United States. Except for some recycling, dysprosium compounds and metal are produced largely outside the domestic supply chain.	China's global market share of mined rare earth compounds has decreased in the past 5 years but is still larger than 50 percent. China's market share of separated heavy REEs such as dysprosium has consistently been more than 80 percent.	Exploration, research and other actions are currently being taken to address the risks for REEs. Ferrodysprosium is currently held in the NDS for national emergency purposes.
Feldspar	Mineral, rock	Feldspar is an abundant mineral that is produced domestically and in many other countries. There are various grades and purity levels which are not always reported separately. One related material, nepheline syenite, is produced domestically but not of sufficient quality to be used in the same applications.	NIR and apparent consumption have fluctuated significantly in the past 5 years, although the top import sources have remained consistent, with Turkey as the main source of feldspar and Canada as the main source of nepheline syenite.	Feldspars are a group of minerals made up of potassium, calcium, and sodium aluminosilicates and are abundant in the Earth's crust.
Fluorspar	Metallurgical grade, acid grade mineral	Metallurgical grade fluorspar is produced in limited quantities domestically. but the United States is completely foreign reliant for acid-grade fluorspar. Fluorspar is not recycled.	Fluorspar supply and demand show few trends, with relatively steady global production and U.S. consumption over the past decade.	Domestic resources for fluorspar are large although geological data are poor. Most imports are from Mexico rather than China, the world's major producer. Fluorosilicic acid is available in the United States, but there is no current pathway to use it as a substitute.

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Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Gallium	Metal, gallium arsenide wafers	The United States is completely foreign reliant for primary gallium and largely from a single country, China. Gallium arsenide wafer imports are also significant and mainly from China.	Over the past decade, refining of gallium has become concentrated in a single country, China. Demand for gallium in wafers in electronics has expanded and grown.	Although domestic primary resources are not likely to become commercial, domestic recycling can be a source of some of the supply. As with many minor metals, data are poor, and better data collection is needed. Exploration, research, and other actions are currently being taken to address supply risks.
Germanium	Oxide, metal, tetrachloride, wafers	Germanium-containing zinc concentrates are produced domestically but exported to Canada for refining. China produces more than one-half of the world's refined germanium.	U.S. NIR has decreased over the past decade. Apparent consumption has also decreased.	Recycling of scrap and imports from Canada can offset reliance on China. Exploration, research, and other actions are currently being taken to address the supply risks.
Gold	Metal	Gold mine production is distributed across dozens of countries, including the United States. The United States is a net exporter of gold.	Gold prices, which can be volatile primarily as a result of its use as an investment commodity, drive production and recycling.	The United States mines and refines gold domestically. The U.S. Department of the Treasury holds significant stocks of gold.
Graphite	Natural, synthetic; amorphous, flake (spherical), lump	The United States is almost entirely dependent on foreign sources, particularly China, for natural graphite.	China mines approximately 75 percent of the world's natural graphite and may have some of the world's largest natural graphite resources. Large graphite projects were ramping up production in Madagascar, Mozambique, and Tanzania.	Recycled refractory graphite is a growing market. Two domestic development projects of natural graphite (in Alaska and Alabama) are underway. Exploration, research, and other actions are currently being taken to address supply risks.
Hafnium	Metal	Hafnium is contained in very small quantities within zirconium ores that are mined domestically. A small fraction of the hafnium that is contained in the ores is recovered and refined commercially to produce hafnium metal domestically.	Trends are difficult to establish in this very small and opaque market.	Only a few countries produce hafnium, and there is very little recycling. However, the United States does have reserves of hafnium contained within the zirconium ores that are mined domestically.

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Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Helium	Crude, refined gas, refined liquid	The United States produces helium as a byproduct of natural gas from wells (not fracking) and refines crude helium at many sites. The United States is the world's leading helium supplier and is a net exporter.	Only a few countries extract helium, including Qatar and Algeria. Supply disruptions have led to volatility in the market over the past decade.	Helium can be collected and recycled, and primary production is tied to natural gas extraction. The U.S. government supplies helium to federal users, including the Department of Defense, National Aeronautics and Space Administration, and many federally funded research institutes. Legislation requires that the U.S. Government dispose of its helium assets by no later than September 30, 2021. These assets include all underground natural resources and the rights to those assets.
Indium	Metal, indium tin oxide, indium phosphide	There is no domestic production of indium and no data on domestic recycling quantities. China and the Republic of Korea combined refine more than two-thirds of the world's indium.	China has been a major producer of indium over the past decade, whereas the Republic of Korea's production has been increasing. Canada has consistently been a significant source of indium, accounting for about one quarter of imports to the United States.	Indium is contained in zinc ores mined in the United States, but it is not refined domestically. Moreover, manufacturing scrap can be a significant source of indium, but no data were available on domestic recycling.
Iodine	Mineral	Iodine is mined and produced domestically by three companies which satisfy about one half of U.S. apparent consumption. Chile produces most of the world's iodine and is a major import source for the United States.	No remarkable changes in the production of iodine have taken place recently.	The United States has notable reserves of iodine and has been consistently producing it over the past decade.
Iridium	Metal	Although iridium is mined in low concentrations from U.S. mines, it is not recovered or refined. Data on iridium are not widely available owing to it being a small market.	South Africa has dominated global production of platinum-group metals (PGMs) for many years largely because it has the world's largest resource for PGMs. Supply shortages have resulted from electricity shortages and other disruptions in South Africa.	PGMs are somewhat substitutable for each other, but less so with other metals. Recycling may be the lowest cost option for domestic sourcing owing to geological scarcity.
Iron and steel precursors	Ore, roasted pyrites, pig iron, direct reduced iron	The United States mines and is a net exporter of iron ore. The United States also produces pig iron and other steel precursors but also imports iron ore and some steel mill products.	Global iron ore production has been increasing, and U.S. production has been relatively stable.	Global and U.S. reserves of iron are large, and resources are many times the size of reserves. Scrap steel is a viable precursor material for most steel goods.
Lanthanum	Mischmetal, lanthanum oxide, carbonate and other compounds, metal	Lanthanum is mined and concentrated domestically, but as with other REEs, lanthanum compounds are produced largely outside the domestic supply chain. Catalyst compounds containing lanthanum are produced domestically.	China's market share of mined rare earth compounds has decreased in the past 5 years but is still greater than 50 percent. U.S. lanthanum oxide production has occurred sporadically within the past decade.	Exploration, research, and other actions are currently being taken to address the risks for REEs.

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Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Lead	Oxides, metal	The United States has multiple lead mines but does not have a single primary refinery. Hence, mined lead is exported for refining outside of the United States. Refined lead is imported from several countries, including Canada, Mexico, and the Republic of Korea.	The last domestic primary lead refinery shut down in 2013, and NIR increased thereafter.	Recycling of automotive batteries is a major source of domestic refined lead.
Lithium	Oxides, carbonates, lithium cobalt dioxide, metal	Although production in the rest of world is large, the United States is still less than 50-percent net import reliant. Production of key lithium chemical compounds used in lithium-ion batteries is concentrated outside the United States	Australia has significantly expanded its lithium mine production capacity in recent years. China has also expanded its lithium mine production capacity and has the largest share of global lithium refinery production.	The domestic lithium-ion battery supply chain is being established and can help offset foreign reliance.
Magnesium	Metal, alloys	The United States produces much of the magnesium metal that it needs to meet apparent consumption but only from a single producer.	Global and U.S. magnesium metal production has generally increased over the past decade. Magnesium castings, primarily for transportation, have grown as an end-use category and are now the predominant use for magnesium metal.	Domestic resources are large, although no published numbers are available. Recycling provides a significant fraction of domestic supply.
Manganese	Metal, alloy, ferromanganese, silicomanganese, oxides, manganates and other compounds	The United States does not mine manganese ore commercially, but imports ore, which is processed mostly to produce steel. Most of manganese imported to the United States in various forms is from African countries. China is the world's leading producer of electrolytic manganese metal.	Global manganese production has generally trended upward over the past decade.	Ore is available from a few countries, such as South Africa, Australia, and Gabon. Manganese is currently held in the NDS for national emergency purposes.
Mica	Sheet, flake, and scrap	Although the United States produces scrap and flake mica, it only produces minor amounts of sheet mica and is almost entirely import reliant for this form of the mineral. Published global production data on sheet mica lists only India and Russia as major producing countries, yet in 2018, the United States imported largely from China.	Global mica production has decreased over time.	Although reserves of scrap and flake mica are large, reserves for sheet mica are very small. Global production data are lacking.
Molybdenum	Molybdenates, metal, ferromo-lybdenum	The United States is a major producer of molybdenum; mining, smelting, and refining the metal domestically. The United States is a net exporter of molybdenum.	Domestic mine production has decreased over the past few years, and Chinese mine production has increased over the past decade.	The United States has large molybdenum reserves to supply primary molybdenum domesti-cally. Recycling is also a source of domestic supply.

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Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Neodymium	Mischmetal, neodymium oxide, carbonate and other compounds, metal, neodymium-iron-boron (NdFeB) magnet alloy	Neodymium is mined and concentrated domestically but, as with other REEs, is separated and refined outside the domestic supply chain. For NdFeB magnets, the supply of sintered magnet block and its precursors is dependent on imports.	China's market share of mined rare earth compounds has decreased in the past 5 years but is still higher than 50 percent. Production outside of China for neodymium compounds and metal has also increased.	Exploration, research, and other actions are currently being taken to address the risks for rare earth elements. Some magnet recycling is performed domestically and could be expanded.
Nickel	Sulphate, chloride, oxide, metal, alloys, ferronickel	A single U.S. mine produced nickel ore that was exported for refining. Data on refined production are not publicly available. The United States is highly net import reliant for refined nickel metal and nickel compounds, with Canada and Australia being major suppliers.	A domestic mine opened in 2014 and produces nickel ore that is exported for smelting and refining. Nickel use in lithium-ion batteries in the form of nickel sulfate has increased in recent years.	The United States has nickel reserves and recycles nickel in the form of ferronickel for steel applications. Many countries mine and refine nickel and could supply the United States.
Niobium	Metal, ferronio-bium, niobium pentoxide, niobium chloride, and other compounds	The United States is completely foreign reliant for primary niobium raw materials and downstream forms such as niobium oxide. Brazil and Canada, combined, produce 98 percent of the global niobium supply. Chinese entities hold a roughly 50 percent equity in global niobium production.	New reinforcing bar (rebar) strength standards implemented by China in 2018 led to increased demand for niobium as a microalloying substi-tute for vanadium in high-strength rebar. Demand for niobium is expected to increase as developing countries construct their infra-structure and developed countries, such as the United States, increase infrastructure redevelopment.	Efforts to develop a domestic supply source of primary niobium are underway; scrap recycling takes places domestically and may be a significant supply source if expanded; ferroniobium and niobium metal are held in the NDS for national emergency purposes
Palladium	Metal	South Africa and Russia, each, produce about one-third of global production. Two domestic mines are in operation, and palladium is refined and recycled domestically.	Domestic production has decreased over the past decade, whereas consumption has remined gener-ally consistent, leading to a recent increase in U.S. NIR.	Two domestic mines contain competi-tive grades of palladium compared with other producers.
Phosphate	Mineral, rock, phosphorus pentoxide, ammonium phosphate	China produces almost one-half of the world's phosphate rock. The United States is the second largest producer and has very low NIR.	World phosphate production has increased over the past decade, tied to increasing demand for agricultural fertilizer and animal feed supplements, the two main end-uses for phosphate rock. China in particular has quadrupled production in the last 15 years.	The United States remains one of the top three producers of phosphate and has significant reserves.
Platinum	Metal	Platinum is one of two PGMs that are mined, refined, and recycled domestically. South Africa dominates global production, and Russia, Zimbabwe, and Canada also produce primary metal.	South Africa has dominated global production of PGMs for many years largely because it has the world's largest resource for PGMs. Global supply shortages have been related to electricity shortages and other disruptions in South Africa.	Platinum grade in the two active domestic mines is lower than palladium grade, but the mines are able to produce commercially.

Table 1. Summary of some of the forms that are produced and traded for each mineral commodity, foreign reliance considerations, trends for the global supply chain, and technical options for the domestic supply chain. Mineral commodities listed include ones with high foreign reliance at some stage in the supply chain. Ores and concentrates are not listed in most cases under the Forms heading but are assumed to be included for all minerals. Data sources include Nassar and others (2020, U.S. Geological Survey (2020a), U.S. Geological Survey (2020b).—Continued

Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Potash	Salt, potassium chloride, potassium sulfate, potassium magnesium sulfate	Domestic production and imports from Canada make up most of the supply for potash consumed in the United States.	Domestic potash production has dropped over the past decade, whereas imports have remained relatively consistent. Potash continues to be used largely as a fertilizer in the agriculture industry.	Potash is produced in many countries, including domestically.
Praseodymium	Mischmetal, praseodymium oxide, carbonate and other compounds, metal, NdFeB magnet alloy	As with other REEs, praseodymium compounds and metal are produced largely outside the domestic supply chain. For NdFeB magnets, which contain praseodymium, up to sintered magnet block, the supply is dependent on imports.	China's market share of mined rare earth compounds has decreased in the past 5 years but is still higher than 50 percent. Production outside of China for praseodymium compounds and metal has also increased.	Exploration, research, and other actions are currently being taken to address the risks for REEs. Some magnet recycling is performed domestically and could be expanded.
Rare earths, others (europium, gadolinium, terbium, holmium, erbium, thulium, ytterbium, lutetium)	SEG+, Heavy REE mix, oxide, metal	These REEs are not produced globally in large quantities and are almost exclusively separated and processed in China. (SEG+ refers to the REEs starting with samarium and going up in molecular weight to lutetium. All are included here except samarium and dysprosium, which are discussed in more detail separately)	New mines have started production within the past decade but the separation process for the lower concentration SEG+ elements remains largely concentrated in China.	Exploration, research, and other actions are currently being taken to address the risks for REEs. SEG is currently held in the NDS for national emergency purposes.
Rhenium	Ammonium perrhenate, metal	Rhenium is recovered domestically from molybdenum concentrates derived from copper deposits. Despite being among the top three producers globally, U.S. consumption of rhenium is large, and imports are needed to meet demand. Chile produces most of the world's rhenium and is a major import source for the United States.	Strong demand for turbines led to price spikes for rhenium in 2008, leading to thrifting in the turbine industry. Rhenium remains a small market whose production is largely tied to molybdenum and copper production rather than to price.	U.S. production of rhenium is tied to mine production of copper and molybdenum. Recycling, especially of new scrap and used turbine parts, is an additional domestic source for rhenium.
Rhodium	Metal	Rhodium is mined in low concentrations from U.S. mines, but the concentrate is exported for recovery in South Africa.	South Africa has dominated global production of mined and refined rhodium for many years largely because it has the world's largest resource for PGMs. Global supply shortages have been related to electricity shortages and other disruptions in South Africa.	PGMs are somewhat substitutable with each other, but less so with other metals. For minor PGMs such as rhodium, recycling may be the lowest cost option for domestic sourcing owing to geological scarcity.
Rubidium	Carbonate, hydroxide, and other compounds, metal	Rubidium is not mined domestically. Trade data do not track rubidium separately.	Trends are difficult to establish in this very small and opaque market.	Almost no data are available on rubidium production. No domestic reserves exist, although it is known to occur in a number of locations. Obtaining better data would the first step to evaluating options.

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Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Ruthenium	Metal	Although ruthenium is mined in low concentrations from U.S. mines, it is not recovered or refined domestically. The concentrate is exported for recovery in South Africa.	South Africa has dominated global production of mined and refined ruthenium for many years largely because it has the world's largest resource for PGMs. Global supply shortages have been related to electricity shortages and other disruptions in South Africa.	PGMs are somewhat substitutable with each other but less so with other metals. Recycling may be the lowest cost option for domestic sourcing, but there is also the possibility of refining ruthenium from the domestic mines that currently produce palladium and platinum.
Samarium	SEG, samarium oxide, metal, samarium cobalt magnet alloy	Only small amounts of samarium are contained in ores mined in the United States and no compounds or metal is produced domestically. samarium-cobalt (SmCo) magnets are produced domestically but require imported samarium alloy, largely from China.	China's market share of mined rare earth compounds has decreased in the past 5 years but is still higher than 50 percent.	Exploration, research and other actions are currently being taken to address the risks for REEs. SEG is currently held in the NDS for national emergency purposes.
Scandium	Oxide, metal	Scandium is produced in only a few countries, predominantly China. Trade data for scandium are combined with trade of the REEs, and production and consumption data are not published.	Scandium production is not thought to be consistent and is mainly a byproduct of other material production. Demand for solid oxide fuel cells that use scandium has led to increased demand.	Insufficient data about scandium reserves is available, but resources are thought to occur in the United States.
Selenium	Oxide, metal	Selenium is mined as a byproduct of copper and is refined domestically at one facility. China is the top producer of selenium worldwide and the leading import source for the United States.	The United States was a net exporter of selenium until 2016. Chinese production has doubled in the past decade.	The United States likely mines more selenium than it recovers because selenium is contained in copper anode slimes. Several countries other than China produce selenium.
Silicon	Metal, ferrosilicon, high-purity silicon	Multiple companies produce ferrosilicon and silicon metal in the United States. China produces more than one-half of the world's silicon but is not a major import source for the U.S.	Silicon production has increased significantly over the past 15 years, with China accounting for a significant fraction of the increase. Silicon in solar applications and electronics are demand growth sectors.	Domestic reserves of silicon are large, with processing being the main cost factor in production. Substitution of silicon for some applications is possible, although many of the substitutes have supply risks of their own.
Silver	Metal	The United States mines, refines, and recycles silver at multiple locations. The United States is still more than 60 percent net import reliant and imports mostly from Mexico and Canada.	U.S. and global production of silver has been generally consistent over the past decade. Silver is also used as an investment metal, which can be a volatile demand category.	The United States has significant reserves of silver, and large stocks are held by the U.S. Treasury. Silver is also highly recyclable.
Steel	Alloy steel, High strength low alloy steel, stainless steel, plain carbon steel, many forms	The United States produces many forms of steel. China is the world's leading steel producer, but the United States imports from many different countries. Some forms of steel may be more critical owing to foreign reliance.	U.S. production of steel has decreased over the past decade, and NIR has slightly increased.	The United States has the capability to produce steel from ore and scrap. Because most steels require alloying elements, the supply of those elements should be considered when examining steel production capability.

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Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Strontium	Oxide, hydroxide, peroxide, carbonate, nitrate, metal	The United States does not mine, process, nor recycle strontium. The world's leading producers are Spain, Mexico, China, and Iran.	Global production of strontium has been decreasing over the past 10 to 15 years, as the result of decreasing global demand. U.S. import levels have been variable.	Deposits of strontium minerals occur in the United States but have not been commercially mined since 1959.
Tantalum	Tantalum pentoxide, potassium heptafluorotantalate (K-salt), carbide, metal, metal powder (standard and capacitor grades), tantalum chloride, and other compounds	The United States is completely foreign reliant for primary tantalum raw materials; the lack of dedicated trade codes for tantalum pentoxide and K-salt (important intermediate forms for the production of capacitor-grade tantalum metal powder) makes it difficult to identify foreign reliance for these materials as well as to fully quantify domestic tantalum consumption	Demand for tantalum capacitors is expected to increase over the next decade corresponding with global electrification rates and the growing demand for high-performance electronic components in applications such as electric vehicles and advanced telecommunications infrastructure.	Domestic resources are not likely to become commercial; scrap recycling takes place domestically and may be a significant supply source if expanded; tantalum metal and carbide powders are held in the NDS for national emergency purposes.
Tellurium	Metal	Tellurium is mined from copper ores and recovered from copper anode slimes in refineries. China produces more than one-half of the world's refined tellurium, but the United States imports primarily from Canada.	Tellurium global production is between 500 and 600 metric tons per year. Over the past decade, China has consistently been the leading producer. Demand for solar photovoltaics has the potential to grow and is thought to be the major end use for tellurium.	Data on tellurium supply and demand are poor and unreliable, making it challenging for evaluating supply risk. Some of the tellurium contained in copper anode slimes produced domestically is thought to be exported for refining to metal outside the United States.
Tin	Oxides, chloride, potassium stannate, metal	The United States has not mined or smelted tin for decades and has no reserves. No single country dominates mine production, and the United States imports from many different countries.	Tin has relatively stable supply and demand.	The United States produces tin from old and new scrap.
Titanium	Mineral concentrates, titanium dioxides, metal (sponge, ingot, billet, powder), ferrotitanium	The United States is a net importer of titanium mineral concentrates, an exporter of titanium dioxide, an importer of titanium metal sponge, and an exporter of titanium ingots. Many countries produce titanium mineral concentrates, but only a few produce titanium metal. The top three sponge producers are China, Japan, and Russia.	Titanium metal demand is linked closely with the aerospace industry, which experienced a major downturn in 2020.	The form of titanium is important to consider in understanding this supply chain. The United States has capacity to produce the various forms of titanium, but it is most vulnerable to foreign reliance on titanium sponge, owing to there being few producers. Titanium metal is recycled domestically and is held in the NDS.
Tungsten	Ammonium paratungstate (APT), oxides, chlorides, tungstates, tungsten carbide, metal, ferrotungsten	The Unites States is complete import reliant for primary tungsten and downstream ammonium paratungstate (APT). U.S. imports from China of APT are very significant.	Tungsten has long been a crucial mineral, especially for defense applications such as military turbine engines and armor-piercing ammunition.	Domestic recycling can offset foreign reliance. Tungsten is also held in the NDS for national emergency purposes.

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Mineral Commodity	Forms	Foreign reliance considerations (based on 2018–19)	Trends (looking back 5 to 15 years)	Technical options
Vanadium	Vanadium pentoxide and other compounds, metal, ferrovanadium, specialty alloys	A single mine in the United States produced vanadium in 2019 as a byproduct of uranium. Vanadium was also recycled domestically, but quantities were not reported. Import reliance is high and China produces just over one-half of the world's mined vanadium.	U.S. vanadium mine production quantity is variable and was zero between 2013 and 2018, although downstream vanadium products were produced domestically with imported feedstock.	Domestic recycling of vanadium could offset as much as 40 percent of demand. Mine production has not been consistent and is mostly a byproduct of steelmaking slags, but reserves are significant.
Yttrium	Yttrium oxide, metal, yttrium stabilized zirconia	Only small amounts of yttrium are contained in ores mined in the United States and no compounds or metal are produced domestically.	China’s market share of mined rare earth compounds has decreased in the past 5 years but is still greater than 50 percent. China's market share of separated yttrium compound production has consistently been greater than 80 percent	Exploration, research, and other actions are currently being taken to address the risks for REEs. Yttrium oxide is currently held in the NDS for national emergency purposes.
Zinc	Oxides, chloride, sulfide and sulfate, metal	Although the United States is a net exporter of mined zinc ore and concentrates, it is highly reliant on imports for refined zinc owing to limited domestic refinery production. Imports of refined zinc are almost all from Canada and Mexico.	Zinc is a major metal commodity and trends have not changed significantly in the past decade.	Mine, refinery, and recycling capacity partially supports domestic demand for zinc. Expansion of current capacity would be dependent on economic conditions.
Zirconium	Oxide, metal (sponge, ingot), ferrozirconium, zirconium oxychloride, fused zirconia	The United States mines zirconium minerals, and two companies produce zirconium metal. The United States does not produce all forms of zirconium, some of which are mostly produced in China.	Trends are difficult to establish in this very small and opaque market.	New scrap can be recycled domestically. Research into more cost-efficient ways to produce some zirconium forms could encourage domestic production of all forms of zirconium.

Summary

The United States is highly net import reliant for a large and growing number of mineral commodities. The increasing net import reliance (NIR) has coincided with a similarly remarkable increase in the concentration of production of many mineral commodities that can be largely attributed to the growth in China’s minerals industry. High import reliance combined with increasing global production concentration may leave even fewer options for import partners in the future.

The countries from which the United States sources its imports vary by mineral commodity. Currently, the United States directly imports most of its consumption of only a small number of mineral commodities directly from China and other nonmarket economy countries. Nevertheless, U.S. imports of most mineral commodities are obtained from a small subset of countries and can be considered moderately or highly concentrated. Moreover, because each mineral commodity supply chain is unique with multiple forms and grades, consideration of import reliance at a detailed level can reveal subsections of the domestic supply chain with higher import reliance than is indicated by the mine-level analysis.

Standard analyses of NIR are further complicated by a variety of factors, including indirect trade reliance, embedded demand, and foreign ownership of mineral assets. The dependency of the United States on foreign sources differs, depending on mineral commodity, from what the standard analyses of NIR reveal. Importantly, NIR in and of itself is not necessarily a cause for concern. In some cases, the United States may currently be a net exporter, but the domestic supply chain may rely on only a single producer, or net exports may be decreasing over time and be on track to become a net import. Moreover, high NIR does not always pose a potential supply risk because it is only one of three components of the risk triangle. Only at the confluence of the three components (hazard, exposure, and vulnerability) of risk does a high degree of risk arise. In turn, reducing any one of these components can reduce the risk of a supply disruption overall.

Various strategies, including those that increase supply such as greater recycling and those that decrease demand such as developing substitute materials, can be adopted to reduce NIR and supply risk. Scenario analysis can be used to determine which strategies are most effective for each mineral commodity supply chain. Because mineral supply chains are complex, unintended or unforeseen circumstances may result from the implementation of any one of these strategies. It will thus be important to examine these options as thoroughly as possible.

The current supply chain configuration is the result of decades long trends in resource exploration, technological development, market adaptation, and price optimization. Policy levers and incentives available to a market economy like that of the United States may therefore also take decades to make a significant impact. Overall, strategies that shift mine to manufacturer supply chains from less stable or less reliable countries to the United States and countries with strong ties to the United States could provide significant improvements in the future security of supply.

References Cited

Alkane Resources Ltd., 2017, High k sourcing & the supply chain of hafnium and zirconium, *in* CMC Conference 2017: Alkane Resources Ltd., Richardson, TX accessed October 15, 2020, at https://cmcfabs.org/wp-content/uploads/2017/05/Alilster_CMCFabs-11-12-May-Alkane-Resources-7-May.pdf.

Alonso, E., Gregory, J., Field, F., and Kirchain, R., 2007, Material Availability and the Supply Chain—Risks, Effects, and Responses: Environmental Science & Technology, v. 41, no. 19, p. 6649–6656. [Also available at https://pubs.acs.org/doi/10.1021/es070159c.]

Binnemans, K., Jones, P.T., Müller, T., and Yurramendi, L., 2018, Rare Earths and the Balance Problem—How to Deal with Changing Markets?: Journal of Sustainable Metallurgy, v. 4, no. 1, p. 126–146. [Also available at http://link.springer.com/10.1007/s40831-018-0162-8.]

Cowell, A., 1981, Zaire's bloody past makes cobalt's future uncertain: New York Times.

Crichton, D., 1999, The risk triangle, *in* Ingleton, J., ed., Natural Disaster Management: London, Tudor Rose, 102-103.

Elshkaki, A., and Graedel, T.E., 2014, Dysprosium, the balance problem, and wind power technology: Applied Energy, v. 136, p. 548–559. [Also available at https://linkinghub.elsevier.com/retrieve/pii/S0306261914010125.]

Fortier, S.M., DeYoung, J.H.J., Sangine, E., and Schnebele, E.K., 2015, Comparison of U.S. net import reliance for nonfuel mineral commodities—A 60-year retrospective (1954–1984–2014): Reston, VA, U.S. Geological Survey. [Also available at https://pubs.er.usgs.gov/publication/fs20153082.]

Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, J., Gambogi, J., and McCullough, E.A., 2018, Draft critical mineral list—Summary of methodology and background information—U.S. Geological Survey technical input document in response to Secretarial Order No. 3359: Reston, VA, U.S. Geological Survey, 15 p. [Also available at https://pubs.er.usgs.gov/publication/ofr20181021.]

Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M.Y., and Zhu, C., 2012, Methodology of metal criticality determination: Environmental Science & Technology, v. 46, no. 2, p. 1063–1070. [Also available at https://pubs.acs.org/doi/10.1021/es203534z.]

Gulley, A.L., McCullough, E.A., and Shedd, K.B., 2019, China's domestic and foreign influence in the global cobalt supply chain: Resources Policy, v. 62, p. 317–323. [Also available at https://linkinghub.elsevier.com/retrieve/pii/S0301420718303490.]

Gulley, A.L., Nassar, N.T., and Xun, S., 2018, China, the United States, and competition for resources that enable emerging technologies: Proceedings of the National Academy of Sciences of the United States of America, v. 115, no. 16, p. 4111–4115. [Also available at http://www.pnas.org/lookup/doi/10.1073/pnas.1717152115.]

Hatayama, H., and Tahara, K., 2018, Adopting an objective approach to criticality assessment—Learning from the past: Resources Policy, v. 55, p. 96–102. [Also available at https://linkinghub.elsevier.com/retrieve/pii/S0301420717302672.]

International Trade Administration, 2020, Countries currently designated by Commerce as non-market economy countries, accessed October 15, 2020, at https://www.trade.gov/nme-countries-list.

Johnson, J., and Graedel, T.E., 2008, The "Hidden" Trade of Metals in the United States: Journal of Industrial Ecology, v. 12, no. 5–6, p. 739–753. [Also available at https://onlinelibrary.wiley.com/doi/full/10.1111/j.1530-9290.2008.00092.x.]

Mancheri, N., Sundaresan, L., and Chandrashekar, S., 2013, Dominating the world: China and the rare earth industry: International Strategic and Security Studies Programme: Bangalore, India, National Institute of Advanced Studies.

Nassar, N.T., Brainard, J., Gulley, A., Manley, R., Matos, G., Lederer, G., Bird, L.R., Pineault, D., Alonso, E., Gambogi, J., and Fortier, S.M., 2020, Evaluating the mineral commodity supply risk of the U.S. manufacturing sector: Science Advances, v. 6, no. 8, eaay8647. [Also available at https://advances.sciencemag.org/lookup/doi/10.1126/sciadv.aay8647.]

Nassar, N.T., Graedel, T.E., and Harper, E.M., 2015, By-product metals are technologically essential but have problematic supply: Science Advances, v. 1, no. 3, e1400180. [Also available at https://advances.sciencemag.org/lookup/doi/10.1126/sciadv.1400180.]

Nassar, N.T., 2015, Limitations to elemental substitution as exemplified by the platinum-group metals: Green Chemistry, v. 17, p. 2226–2235. [Also available at http://xlink.rsc.org/?DOI=C4GC02197E.]

Office of the United States Trade Representative, 2020, Free Trade Agreements, accessed October 15, 2020, at https://ustr.gov/trade-agreements/free-trade-agreements.

Roskill Information Services Ltd., 2018, Natural and synthetic graphite—Global industry, markets and outlook, 2018: London, UK, Roskill Information Services Ltd., 504 p.

S&P Global Market Intelligence, 2020, Metals and mining database, accessed October 15, 2020, at https://www.spglobal.com/marketintelligence/en/campaigns/metals-mining.

Schnebele, E., Jaiswal, K., Luco, N., and Nassar, N.T., 2019, Natural hazards and mineral commodity supply—Quantifying risk of earthquake disruption to South American copper supply: Resources Policy, v. 63, p. 101430. [Also available at https://linkinghub.elsevier.com/retrieve/pii/S0301420718306676.]

U.S. Census Bureau, 2020a, Guide to Foreign Trade Statistics, accessed October 15, 2020, at https://www.census.gov/foreign-trade/guide/sec2.html#country.

U.S. Census Bureau, 2020b, USA Trade Online, accessed October 1, 2020, at https://usatrade.census.gov/.

U.S. Department of Commerce, 2019, A federal strategy to ensure secure and reliable supplies of critical minerals: Washington, D.C., U.S. Department of Commerce. [Also available at https://www.commerce.gov/sites/default/files/2020-01/Critical_Minerals_Strategy_Final.pdf.]

U.S. Department of Defense, 2019, Strategic and critical materials 2019 report on stockpile requirements: Arlington, VA, Office of the Under Secretary of Defense for Acquisition and Sustainment, U.S. Department of Defense.

U.S. Department of Defense, 2020, Security of Supply, accessed October 15, 2020, at https://www.businessdefense.gov/security-of-supply/.

U.S. Department of Justice and Federal Trade Commission, 2010, Horizontal merger guidelines, accessed October 26, 2020, at https://www.justice.gov/sites/default/files/atr/legacy/2010/08/19/hmg-2010.pdf.

U.S. Department of State, 2017, U.S. Collective Defense Arrangements, accessed October 15, 2020, at https://2009-2017.state.gov/s/l/treaty/collectivedefense/index.htm.

U.S. Geological Survey, 2020a, Minerals yearbook: Reston, VA, U.S. Geological Survey. [Also available at https://www.usgs.gov/centers/nmic/minerals-yearbook-metals-and-minerals.]

U.S. Geological Survey, 2020b, Mineral commodity summaries 2020: Reston, VA, U.S. Geological Survey, 204 p. [Also available at http://pubs.er.usgs.gov/publication/mcs2020.]

U.S. National Science and Technology Council, 2016, Assessment of critical minerals—Screening methodology and initial application: Washington, D.C., U.S. Office of Science and Technology Policy, Executive Office of the President. [Also available at https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/NSTC/csmsc_assessment_of_critical_minerals_report_2016-03-16_final.pdf.]

Appendix 1 Mineral Commodity Narratives

This section provides a high-level overview of the key factors that determine supply risks for each of the materials highlighted in the previous section. Data sources include Nassar and others (2020), U.S. Census Bureau (2020), U.S. Geological Survey (2020a), and U.S. Geological Survey (2020b).

Alumina and Bauxite–Nonmetallurgical Applications

Bauxite and alumina are not just used to produce aluminum metal. These industrial minerals are also used as abrasives, refractories, chemicals, and other precursor materials. The grades required for nonmetallurgical applications are generally less stringent than those for production of metal and cannot be used interchangeably with metallurgical bauxite and alumina.

Data clearly identifying production of bauxite and alumina by grade are not widely available at a global level. Within the domestic supply chain, nonmetallurgical bauxite and various grades of alumina are produced and consumed. Import reliance is relatively high but is distributed among various countries, including Jamaica, Brazil, Australia, Canada, and Guinea. It is possible that some specialty grades have high import reliance, which requires additional data for further assessment.

Aluminum – Bauxite, Alumina and Metal

Aluminum is the second most produced metal mineral commodity by annual tonnage, after iron (steel). The aluminum supply chain begins with the mining of bauxite ore, followed by processing to alumina, and then smelting and refining to aluminum metal. Aluminum metal is highly recycled, a process that saves energy and cost. Aluminum is finally alloyed and shaped to the hundreds of aluminum alloys and forms used across many economic sectors. These include construction, automotive, aerospace, energy, machinery, appliances, furniture, and packaging. Although properties vary depending on the alloy, generally, aluminum has a high strength-to-weight ratio and is a good conductor of heat and electricity.

Not all grades of bauxite and alumina can be used in the production of aluminum metal, and those grades are discussed separately. All the bauxite that is used to produce alumina and aluminum in the United States is imported, primarily from Jamaica. Global production of bauxite is split across various continents, including Africa, Asia, Australia, and South America. The United States produces less than 5 percent of the world's alumina supply and is dependent on imported alumina for the production of aluminum. Although China is the world's leading producer of alumina, accounting for just over one-half of the world's production, the United States imports mostly from Brazil, Australia, and Jamaica. Another precursor material for aluminum production is aluminum fluoride, for which the United States is also significantly import reliant.

For the actual production of aluminum metal, China is the world's leading producer, having tripled its primary production between 2007 and 2018. Over the same period, China also quadrupled its production of secondary aluminum. Although U.S. secondary production has been steady over that time period, primary production has decreased by more than 50 percent. Moreover, certain forms of aluminum are more technically difficult to make, and domestic capability for production may be lost or declining. These concerns warrant additional attention.

Antimony

Antimony metal is used in ammunition and lead-acid batteries as well as other lead alloys. Antimony is used in nonmetallic form in ceramics, glass, and rubber products and in flame retardants.

Although domestic resources of antimony ore have been commercially mined in the past 10 years, no mine production was reported in 2020. Some primary and secondary smelter production took place. Refinery production occurs with imported feedstock of concentrates and oxides, largely from China, which is also the world's leading concentrate producer. However, Chinese production has decreased over the past 10 years. Russia and Tajikistan, now the second- and third-ranked producers, respectively, have increased antimony production.

Arsenic

The largest application for arsenic is for wood preservation and pesticides, where arsenic trioxide is used to produce arsenic acids that are then formulated into chromated copper arsenide. In metal form, arsenic is used in alloys and in semiconductors, such as gallium arsenide, indium gallium arsenide, and germanium arsenide selenide which are used in electronics for integrated circuits, solar cells, telecommunications, and specialty optical materials.

Arsenic is very common in the Earth's crust and could be produced at many base and precious metal mines, based on arsenic concentration in the ore. However, it is not profitable; therefore, the arsenic is usually discarded. China produces more than one-half of the world's arsenic trioxide, and although no data were available on China's production of arsenic metal, it is the source of more than 90 percent of imports to the United States. The United States has no domestic production and has not produced any arsenic for years except for limited recycling of scrap generated during gallium arsenide manufacturing. However, arsenic is potentially recoverable from domestic smelter residues because it is found in domestic ores, albeit in low concentrations.

Barite

Barite, or barium sulfate, is an insoluble mineral that is used predominantly as a weighting agent and filler material in drilling fluids in the oil and gas industry. Although alternative materials are available, barite is the material of choice for that application. Barite also is used in the production of plastics, rubbers, glass, and paint, as well as a in a few niche applications where substitution may be more challenging.

Reserves data are not available for the United States, but barite is produced at a few mines. Production quantities are sufficient to meet only a small fraction of domestic demand, and most of demand is met by imports. About a dozen countries mine barite, although China and India, combined, produce about one-half of the world's barite. More than one-half of imports to the United States are from China, with the rest coming mostly from India, Morocco, and Mexico.

Beryllium

Beryllium metal is crucial for defense applications such as radar, electronic countermeasures systems, telecommunications satellites, infrared target acquisition systems, and surveillance systems. It is also alloyed with copper for commercial applications such as underwater pressure vessels, aircraft landing gear, telecommunications, shielding, and electronic connectors. Although beryllium is toxic, limiting how it can be handled, it has properties that make it highly desirable; therefore, substitution is very challenging in the applications where it is used, especially for defense.

The United States dominates global beryllium mine and metal production, with only a handful of other countries producing beryllium. China is the world's second ranked producer of beryllium but produces less than a one-third the quantity produced by the United States. All U.S. primary production of beryllium is from a single company, which received Federal Government funding to build a primary beryllium facility. Beryllium is also held in the National Defense Stockpile (NDS) for national emergency purposes. Some recycling of beryllium is possible and currently practiced, although the quantity is not reported.

Bismuth

For many of its end uses, bismuth is combined with other metals and compounds, making it difficult to track quantitatively through the supply chain. One of the major end uses is in pharmaceutical applications, where bismuth is used to treat acid reflux, stomach ulcers, burns, and intestinal disorders. Another end use is in metal form as a nontoxic substitute for lead in pipe fittings, water meters, and other plumbing applications. Bismuth is also used in small quantities in a wide variety of applications such as ceramic glazes, crystal ware, triggering mechanisms for fire sprinklers, and some semiconductor devices.

On the supply side, domestically, bismuth is contained in and mined with lead. However, it is not recovered or processed domestically. Small amounts are recycled, specifically bismuth-containing alloy scrap, but no recycling is possible for many of bismuth's applications such as for pharmaceuticals. As a result, the domestic supply chain is mostly reliant on imports, which are largely from China, the world's leading producer of bismuth metal and compounds. Alternative producers include Laos, the Republic of Korea, Japan, and Mexico.

Cerium

The most common of the rare earth elements (REEs), cerium is used in a broad range of applications, including glass polishing, catalytic converters for vehicles with internal combustion engines, fluid cracking catalysts, glass for display screens, and as an iron and steelmaking additive. Lanthanum is often used in similar applications to those for cerium but is not a perfect substitute. Domestic manufacturing for catalysts and iron and steel require cerium oxide feedstock.

Although the United States has cerium resources, and mines and concentrates rare earth ores with high cerium content, the concentrates are exported to China for separation and refining. Complete separation is not needed for all applications, but even mischmetal, which is a mix of light REEs, especially lanthanum and cerium, is not produced domestically. It is only after these additional steps of the supply chain, currently done predominantly in China, that catalyst, glass, and iron and steel makers can use the cerium for their manufacturing processes.

Many efforts to build and support the domestic rare earth supply chain are underway. Production of separated cerium compounds from a domestic mine occurred within the past decade and could potentially start again.

Chromium

Chromite ore is used to make chromium metal and ferrochromium but also to make chromium chemicals used in leather tanning, metal finishing, pigments, ceramics, and wood preservation. Steel, especially stainless steel, is the main end use for ferrochromium, and superalloys are the main end use for chromium metal. Uses for steel span the entire economy. For example, stainless steel applications include electrical appliances; chemical, and oil and gas industrial equipment; cutlery; and medical devices. Other steels that use chromium such as full-alloy and heat-resistant steels are used in transportation and defense. Superalloys are largely used in turbine engines for aerospace and land-based energy generation applications. Few, if any, substitution options exist for chromium in stainless steels and superalloys.

Chromite ore is not mined domestically; imports are mainly from South Africa, the world's leading producer of mined chromium. Chromite is domestically used for chemical applications rather than for smelting and refining to chromium metal. Chromium metal and ferrochromium are not produced domestically. Chromium contained in steel can be recycled into steel products and offsets some of the chromium import requirements. Most of the imports of chromium to the United States are in the form of ferrochromium, of which one-half are from South Africa, the world's leading producer of ferrochromium. Kazakhstan, Finland, India, Zimbabwe, and Russia are also sources of ferrochromium imports to the United States. Chromium metal imports to the United States are small compared with the ferrochromium imports and are largely from Russia, the United Kingdom, and China. Russia is the world's leading producer of chromium metal. The NDS holds ferrochromium and chromium metal for national emergency purposes.

Cobalt

Cobalt is well known for its use in rechargeable batteries for consumer electronics and electric vehicles. The latter application now represents the leading global use. In contrast, most domestic consumption of cobalt is in superalloys for gas turbine engines, cemented carbides, magnets, specialty steels and various chemical applications. Cobalt provides specific performance advantages (for example, high strength, corrosion resistance, or cycle stability) in many of these applications, and substitutions, when possible, may increase cost.

Most mined cobalt, approximately 70 percent, is supplied by the D.R. Congo as a co-product or byproduct of copper or nickel production. Similarly, refinery production is extremely concentrated. China is the world's leading producer of refined cobalt and imports cobalt from mining countries to meet its refinery demand. The United States is not highly dependent on China to fulfill its overall cobalt demand because domestic consumption is largely unwrought cobalt metal, and China principally exports cobalt powder and cobalt hydroxide. Only about one-tenth of cobalt imports (in all forms) to the United States come from China. Instead, the United States is reliant on a variety of other exporting countries, including Norway and Japan.

Domestic reserves, production, refining and processing are limited. U.S. reserves represent less than 1 percent of world reserves, and production is less than or equal to 1 percent of global mine production. Cobalt concentrates are not refined domestically; however, some chemical processing of cobalt intermediates does occur. Domestic recycling capabilities exist, and cobalt contained in purchased scrap represented more than one-quarter of reported consumption.

Fluorspar

Fluorspar, the mineral form of calcium fluoride, is generally subdivided into two grades that do not substitute for each other: metallurgical grade and acid grade. Fluorspar is used in the production of many other materials, including aluminum, steel, glass, and cement, as well as in precursor chemicals, fluorocarbons, and fluoropolymers. The importance of fluorspar is difficult to gage but is clearly significant because these materials are used across many industrial sectors, including construction, transportation, electronics, and healthcare. U.S. apparent consumption fluctuates from year to year with generally lower consumption in the past few years compared with that of a decade ago.

Domestic resources are large but not well quantified. Although some limited domestic production of metallurgical-grade fluorspar takes place, no acid-grade fluorspar is produced domestically. Although China produces more than one-half of the world's fluorspar, the United States sources most of its imports from Mexico, and supply has been stable.

Gallium

Although world production of gallium is less than 500 metric tons annually, this minor metal is crucial to the functioning of many electronic applications, including integrated circuits for satellite communications. In many applications, gallium provides high-efficiency, high-frequency, high-power, and low-noise properties that make substitution with other materials difficult.

Crude gallium is largely extracted as a byproduct of bauxite and alumina refining. It is also extracted as a byproduct of zinc. Most alumina and zinc refiners do not capture it, and crude gallium is not produced domestically. China produces almost all the world's crude gallium and is the primary source of the gallium imported by the United States. China also is the source of most of the gallium arsenide wafers imported into the U.S. Over the past 10 years, Chinese production of crude gallium has increased. China's market share has increased to the point that alternative primary sources of gallium are increasingly limited. China also produces most of the world's refined and high-purity gallium and has been moving to increase its market share.

However, the domestic supply chain refines imported crude gallium into high-purity gallium. In addition, secondary sources include domestic production and production from countries such as Canada, Germany, and Japan.

Germanium

Germanium is a semiconductor material that is crucial for several applications, including infrared optics, fiber optics, and solar photovoltaic cells for satellites, and as a catalyst in the manufacturing of polyethylene terephthalate (PET), a precursor to polyesters and packaging plastics. A number of these applications are important for defense applications.

Understanding the supply chain for minor metals such as germanium, for which global production is less than 200 metric tons annually, is challenging owing to poor data availability. Germanium is mined as a byproduct of zinc and must be separated and refined from the germanium-containing zinc concentrates. China produces more than one-half of the world's refined germanium and is also a major import source of the metal to the United States, which is heavily reliant on imports.

Domestic reserves data are not available, but germanium-containing zinc concentrates were mined at multiple sites domestically; some concentrates were exported to a refinery in Canada to process and recover the germanium. Recycling at a refinery in Oklahoma also produced germanium compounds to be used in fiber optics.

Graphite

Graphite is increasingly becoming an essential component in high technology applications, especially energy technologies, including battery anodes, fuel cells, solar cells, and pebble-bed nuclear reactors. More traditional uses of graphite are associated with the ferrous and nonferrous metal manufacturing industries; major consuming applications include electrodes, refractories, and foundries.

Importantly, newer and more traditional applications consume very different forms of graphite. Graphite is available in natural and synthetic forms. Natural graphite can be classified into three types: amorphous, flake, and lump, which in turn can be further processed and treated to create specialty or higher-grade products (for example, spherical graphite). Examples of the specificity by application include battery anodes, which require spherical graphite; electrodes, which require synthetic graphite, and most refractories, which require natural flake. This specificity is important when considering import reliance.

Production of natural and synthetic graphite is highly concentrated in China, one of the leading producers, exporters, and consumers of both forms. Furthermore, the country produces almost all the spherical graphite used in batteries. In terms of imports, the United States is highly dependent on graphite (all forms) from China. However, current U.S. consumption of synthetic graphite is largely satisfied by domestic production, which is robust (the United States is a major synthetic producer). In contrast, no natural graphite is produced domestically; although, several U.S. deposits are under development (including one in Alabama and one in Alaska). Consequently, for domestic uses requiring natural graphite, most imports come from China.

Helium

Helium gas was a crucial gas for defense applications during World War II, owing to its low density and inert properties. Although it remains crucial for defense applications, other end uses have been developed, including aerospace, welding, and cryogenic (such as in medicine and research) applications. No good substitutes exist for helium in cryogenic applications as well as in some defense and aeronautics applications.

Most commercial helium is extracted as a byproduct of natural gas from traditional natural gas drilling operations; however, some helium deposits contain little or no hydrocarbons. The United States has historically been, and continues to be, the leading global producer and supplier of helium. In the past 20 years, Qatar started, and is expanding, its helium extraction capacity; it is currently the world's second-ranked producer. However, supply from Qatar has been unreliable, not because the helium production itself was disrupted, but because of border closings owing to political unrest in the region. Unlike other commodities, helium must be transported in special containers, which can hold the helium for only a limited amount of time before the gas contained must be let out (and thus lost), and the containers must be returned to the production site once the helium within has been either transferred or consumed. Thus, delays in transportation of helium containers to and from end users were compounded, and losses in transit meant that, for each container shipped, less gas was ultimately delivered to the end users.

Commercial, academic, and government end users, including the U.S. Government, have needed to find ways to deal with uncertainty in the supply of helium. With the proper equipment, helium can be captured and recycled in many end uses, such as in research and medical applications. The U.S. Government owned a large helium reserve, which provided a reliable supply of domestic helium and served as a storage space for excess helium. However, legislation enacted in 2013 required the U.S. Government to dispose of its helium assets by no later than September 30, 2021. These assets include all underground natural resources and the rights to those assets at the Cliffside Field in Texas.

Indium

Indium's most important application is in the form of indium tin oxide, a transparent, electrically conductive coating used in touch screens, lighting, and other electronic applications. Indium metal also is used domestically in solders, which are used in many manufacturing processes. One of the new demand areas for indium is in solar photovoltaics, which are used to produce electricity in residential and commercial areas as well as for larger-scale production connected to the electrical grid.

Indium is most commonly produced from zinc residues generated during zinc ore processing. No indium refinery production takes place domestically, and any recycling is not reported quantitatively, so NIR is estimated to be 100 percent. China is a major global refiner of indium, although the Republic of Korea has been increasing production over the past decade. Canada has had steady refinery production and is a significant import source for the United States.

Iridium

As with other platinum-group metals (PGMs), iridium is expensive and used in applications where its unique properties justify the cost. It is crucial for certain industrial processes as a catalyst and electrode. It is used, for example, in the production of chlorine and sodium hydroxide, for crucibles where it is used to grow high-purity single crystals for LEDs, and in automotive spark plug tips.

Iridium is one of the minor platinum group metals, and data on its supply and demand are difficult to obtain. The domestic supply of iridium consists of only in minor quantities from the mining of platinum and palladium, but it is not separated or refined domestically. Therefore effectively, NIR is 100 percent. South Africa produces most of the world's mined iridium. Refinery production data are unavailable, although the United States does import from South Africa, the United Kingdom, Germany, and a few other countries. Recycling is technically feasible, but aside from global model estimates (Nassar, 2015), data on iridium recycling are generally not available.

Lanthanum

Lanthanum is the second-most common of the REEs and is used in similar applications to those of cerium, but lanthanum has slightly different properties and cannot be used interchangeably with cerium. Lanthanum's main end use is in fluid cracking catalysts. The second key application is in nickel metal hydride rechargeable battery cathodes, where only limited cerium is used. Lanthanum is also used in automotive catalytic converters.

Although the United States has lanthanum resources and mines, and concentrates rare earth ores with high lanthanum content, the concentrates are exported for separation and refining to China. Complete separation of lanthanum to its elemental oxide is not needed for all applications, but even mischmetal, which is a mix of light REEs, especially lanthanum and cerium, is not produced domestically. Domestic manufacturing of catalysts is robust but requires imports of lanthanum, cerium, and (or) mischmetal. Imports are mostly from China, the world's leading producer of REEs at the mining, extraction, and separation stages.

As with other REEs, efforts are underway to build and support the domestic rare earth supply chain. Production of separated lanthanum compounds from a domestic mine occurred within the past decade and could potentially restart.

Lithium

Globally, the largest market for lithium products was batteries, followed by ceramics and glass, and lubricating greases. World consumption of lithium has grown steadily over the last decade, especially in recent years as use in batteries has significantly increased.

Lithium is extracted from two sources—brine operations and hardrock ores—and then processed into a variety of compounds, including lithium carbonate, chloride, and hydroxide. The United States has one producing brine operation in Nevada and two producers of lithium compounds. The United States relies primarily on Argentina and Chile for lithium carbonate imports, and slightly on China for lithium hydroxide. The United States is actually a net exporter of lithium hydroxide. World production of lithium has exceeded demand in recent years, and prices have fallen, leading to different operational responses. Existing producers have paused capacity expansion, whereas in some cases, new producers have shut down.

Increasingly, lithium metal and lithium-ion batteries are being recycled, and new technologies for recycling are under development.

Magnesium

Approximately one-half of magnesium metal produced is used for castings in applications where magnesium's high strength-to-weight ratio is important, such as in the automotive industry. This end-use category has grown over the past decade. Magnesium metal has poor formability, but when alloyed with aluminum, it is commonly used for packaging and transportation. Magnesium compounds have very different uses than the metal and are predominantly used in refractory, fertilizers and animal feed, wastewater treatment, flooring tiles in construction, and several chemical industries.

Magnesium is the eighth most abundant element in Earth's crust, but the process to produce metal is energy intensive and technically challenging and therefore quite costly. Only a fraction of magnesium mined is turned into metal; most is used in the form of compounds. Domestic production of magnesium metal occurs in a single plant sourcing magnesium from brine. Production from that plant plus recycling (from domestic and imported scrap) produce more than one-half of the magnesium metal consumed domestically. China produces more than 85 percent of the world's magnesium using a process that is known to be environmentally destructive, but inexpensive. Production at larger scale and ongoing technological improvements have made it possible for the United States to remain competitive with China.

Manganese

Almost all manganese is used in iron and steel production, consumed either in the form of ore or as a ferroalloy. In steelmaking, manganese is indispensable. Steel, the most produced metal in terms of annual tonnage, is used across every economic sector from construction to transportation to machinery. In nonsteel applications, manganese is used in some rechargeable lithium-ion batteries, alkaline batteries, and lithium-manganese-dioxide nonrechargeable batteries. Also, electrolytic manganese metal, which is manganese metal with 99 percent or greater purity, is a special form of manganese used in nonferrous alloys such as aluminum alloys used for aerospace and other transportation applications.

Manganese ore is not mined domestically. The United States imports all manganese that is consumed by the domestic supply chain, whether to produce steel or to produce various forms of manganese such as ferromanganese, silicomanganese, and manganese chemical compounds. In terms of ore, import source options are varied, with Australia, Brazil, China, Gabon, Ghana, India, and South Africa among the many producers of manganese ore. In terms of electrolytic manganese metal, imports options are very limited with China dominating global production, and only South Africa as a known alternative supplier. The NDS holds manganese ore and ferromanganese and currently has the authority to purchase electrolytic manganese metal.

Neodymium

Neodymium, one of the light REEs, has strong magnetic properties. Alloyed with iron and boron and several other elements such as praseodymium, dysprosium, cobalt, and niobium, neodymium-iron-boron (NdFeB) permanent magnets are the strongest, lightest permanent magnets that are commercially available. These magnets are used across many industrial sectors, including energy, transportation, electronics, medical equipment, and industrial machinery. Although magnets are its main end use, neodymium also is used in catalysts, some metal alloys, and ceramics.

Supply for neodymium is tied to the supply of other light REEs. In some applications, neodymium is not fully separated and simply used in rare earth mixes, such as in mischmetal and a mix of neodymium and praseodymium (Nd/Pr) that can be used to make magnet alloys. China produces most of the REEs mined globally, but neodymium is mined outside of China, including in the United States and Australia. It is separated in Malaysia. However, separation capacity is being rebuilt in the United States. Magnet recycling capability is growing domestically and currently supplies some magnet material to the domestic supply chain.

Options for improving the domestic supply chain for neodymium include resource exploration and development, recycling, and research into substitution and improved efficiency of use. Ongoing efforts to build a domestic supply chain are broad and consider the full mine-to-magnet supply chain.

Niobium

The primary use for niobium is as an alloying element in high strength-low alloy steel for automobiles, gas pipelines, and heavy engineering and construction (such as in reinforcing bars or "rebar"). Other major applications for niobium include use as an alloying element in high-performance alloys for aircraft engines and land-based industrial gas turbines and as metal and niobium-based alloys for superconductors in particle accelerators and magnetic resonance imaging (MRI) machines.

Niobium production is heavily concentrated in Brazil. Domestic niobium resources are of low grade, and the United States is entirely reliant on foreign sources for its supply of primary niobium as well as intermediate forms of niobium such as ferroniobium and niobium pentoxide (Nb_2O_5). Chinese entities own approximately 50-percent equity in global niobium production via the two largest Brazilian producers. Major niobium suppliers to the United States include Brazil, Canada, and Russia. No domestic processors recover niobium from raw materials, although several processors recover niobium from scrap and recycled materials. Options for improving the domestic supply chain for niobium include resource development, recycling, research into substitution, and improved efficiency of use. Efforts are underway to develop a domestic supply chain for niobium. The NDS holds ferroniobium and niobium metal ingots.

Palladium

Palladium is mostly used with platinum and rhodium in automotive applications where its catalytic properties are used to reduce automotive emissions, especially in gasoline-powered vehicles. Palladium also is used in electronics such as on printed circuit boards, in dental alloys, and as a chemical process catalyst. It is somewhat substitutable with platinum.

The domestic PGM mines contain more palladium than platinum, and U.S. import reliance for palladium is the lowest for the PGMs. Imports to the United States are mostly from South Africa and Russia, the two leading producers of palladium. Imports also are sourced from several European countries where refined production occurs.

As with platinum, mining and recycling of palladium occurs domestically. Both domestic mines have significant reserves to supply production in the future.

Platinum

Although platinum is used in jewelry and as an investment metal, it is primarily used in several critical industrial processes and is valued for its catalytic properties. In addition to being used in vehicles with internal combustion engines in the catalytic converter (typically more common in diesel- than gasoline-powered vehicles), it is used in the petrochemical industry for petroleum refining (reforming and isomerization), in chemical manufacturing for processes such as the production of medical-grade silicones, and in the pharmaceuticals for the production of antibiotics and medicines. Demand for platinum has the potential to increase if fuel cell use increases. Investment-grade platinum is usually in the form of ingot and coin, and industrial users prefer the metal in sponge form.

South Africa mines almost three-quarters of the world's platinum, with Russia, Zimbabwe, the United States, and Canada mining most of the remaining platinum, listed in rank order of quantity mined. South Africa refines a significant amount of platinum, and Europe, North America, and Russia also have refining capacity. The United States produces mined and recycled platinum, and most of its imports come from South Africa. Two domestic mines supply concentrate to a single domestic smelting and refining facility that produces platinum and palladium filter cake. The domestic smelting and refining facility also recycles spent automotive catalytic converters, which are processed into the PGM-rich filter cake form. Both domestic mines have significant reserves to supply production in the future.

Potash

Potash is a commodity that encompasses several mined and manufactured salts that contain the element potassium in water-soluble form. Potassium is a critical nutrient for agriculture and is used in various forms in fertilizers. Potash cannot be recycled, but modified farming practices can be used that require less added fertilizer.

The United States produces only a small fraction of the potash needed to meet domestic agricultural consumption and is highly import reliant. However, several countries produce potash, and Canada is the world's leading producer and the dominant import source for the United States. U.S. reserves and resources of potash are very large relative to current consumption.

Praseodymium

Praseodymium, one of the light REEs, is generally used alongside neodymium, especially in NdFeB permanent magnets. In fact, NdFeB magnets generally contain about 5-percent praseodymium that is added to the magnet alloy to lower cost while maintaining strong magnetic properties. NdFeB magnets are critical across many industrial sectors, including energy, transportation, electronics, medical equipment, and industrial machinery. Praseodymium's minor applications include pigments and glazes, primarily for ceramics.

Supply of praseodymium is tied to the supply of other light REEs. In some cases, praseodymium is not fully separated and is used in rare earth mixes, such as in mischmetal and Nd/Pr mix. China controls most of the market share, but praseodymium is mined outside China, including in the United States and Australia. It is separated in Malaysia, and capacity is being rebuilt in the United States. Magnet recycling capability is growing domestically and supplies some magnet material to the domestic supply chain.

Options for improving the domestic supply chain for praseodymium include resource exploration and development, recycling, and research into substitution and improved efficiency of use. Ongoing efforts to build a domestic supply chain are broad and consider the full mine-to-magnet supply chain.

Rare Earth Elements, Remaining Elements

The term "rare earth elements" refers to a group of elements in the periodic table consisting of the lanthanide series (atomic numbers 57–71). Often, scandium (atomic number 21) and yttrium (atomic number 39) are included. In these narratives, cerium, lanthanum, neodymium, praseodymium, samarium, yttrium, and scandium have been discussed separately, and this section will focus on the remaining REEs, which are europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Other than samarium, these are the elements included in what is sometimes referred to as SEG+. These are also sometimes called the mid and heavy REEs. SEG refers to samarium, europium, and gadolinium only.

By weight, these elements account for only 5–6 percent of the total REEs mined, extracted, and separated. However, they are critical for certain niche applications, and in many cases, the best-known substitution options are other REEs.

By weight, rare earth permanent magnets are the largest end use for these REEs. In particular, gadolinium, terbium, and dysprosium are used to enhance magnet properties for a subset of NdFeB magnets and samarium-cobalt (SmCo) magnets. Although 10 years ago, options for substitution were lacking for dysprosium use in NdFeB permanent magnets, research efforts, such as the use of grain boundary diffusion methods for production of sintered magnets, have succeeded in decreasing the amount of dysprosium needed.

Gadolinium, erbium, and holmium are commonly used in specialty glass for lasers and fiber optics and for optical glass for lenses used in cameras, microscopes, binoculars, telescopes, and other devices. Europium, gadolinium, terbium, thulium, and lutetium are used in phosphors that are then incorporated into general lighting and backlighting on screens for electronic applications. Other applications include magnetostrictive alloys, such as terfenol-D used in impact sensors and audio transducers, fiber amplifiers, MRI contrasting agents, magnetic refrigeration, and other specialty alloys.

All the REEs are produced predominantly in China. These elements are found in small concentrations in most of the commonly mined rare earth ore bodies containing traditional rare earth minerals such as bastnaesite and (or) monazite. Even in minerals that are rich in heavy rare-earth elements, such as ion adsorption clays found in southern China, the concentration is still less than 50 percent (note yttrium is not included in this section but is often included in the “heavy rare earth” group). Separating these elements from the rest of the REEs is easier than separating them from each other. As a result, fewer commercial processing plants are able to separate the elements of SEG+ than are able to separate the four lightest REEs (cerium, lanthanum, neodymium, praseodymium).

The challenges in addressing the risks of foreign reliance for REEs, especially these mid to heavy REEs, are significant and are part of a large ongoing effort within the U.S. Government. Addressing the risks is part of the NDS Program, which has purchased SEG for use in a national emergency.

Rhenium

Rhenium is a critical alloying element used in superalloys, which are largely used in commercial and defense aerospace and industrial gas turbines. The United States is a major producer of superalloys and of turbines, consuming a large fraction of the global rhenium production. Rhenium is also used as an industrial catalyst (particularly in petroleum reforming as a cocatalyst with platinum), in high-frequency electronic equipment and other electronic components, in crucibles for high temperature melts, in electron tubes and targets, and in thermocouples.

The United States produces primary and secondary rhenium but not in sufficient quantities to meet domestic demand. Primary rhenium is produced as a byproduct during the roasting of molybdenite concentrates, which are produced from porphyry copper-molybdenum ores deposits mined in several U.S. States. Owing to a lack of specialized capability, a notable portion of rhenium-containing, unroasted molybdenite concentrates were exported to other countries where rhenium is recovered, and a portion of the exports was reimported to the United States as rhenium metal. Nearly one-half of the imports are from Chile, and other countries such as Germany, Canada, Kazakhstan, and Poland have supplied the rest of the imports to the United States. Chile produces most of the world’s rhenium, with Poland and the United States producing significant quantities as well. The quantity recycled in the Unites States from spent catalysts, superalloy foundry scrap revert (new scrap), and end-of-life gas turbine parts is thought to be significant, but data were not reported. Reserves of rhenium are large compared to annual production.

Rhodium

The largest end-use for rhodium is in automotive catalytic converters, where it is particularly effective at reducing emissions of nitrogen oxides (NO_x), for which European Union standards are particularly stringent. Its high melting point is critical in glassmaking where it is used to line crucibles and in some electrical and chemical applications.

South Africa is the world’s leading producer of rhodium with about 80 percent of world production, followed by Russia. Most imports into the United States are from South Africa. The United States also imports from European countries that either may be buying lower grade material and refining it to higher purity or are producing from scrap.

Rhodium is one of the most expensive metals produced and generally the most expensive of the PGMs. Its high cost, coupled with price volatility, results in limited use in commercial applications because, where possible, thrifting and alternative substitutes will be selected. In many of its applications, possible substitutes are other PGMs, which are also expensive. Although recycling is challenging because the process is more time consuming and costly than that for platinum and palladium, it is likely the most feasible option for the domestic supply chain.

Ruthenium

Ruthenium is a minor PGM that is used in similar applications to other PGMs, in particular as an industrial catalyst and for electrical applications. It may be alloyed with platinum and palladium to improve their hardness.

As with rhodium and iridium, ruthenium is found in very small quantities in ores containing platinum and palladium. South Africa hosts the world's richest and highest quality reserves for PGMs and dominates global production for ruthenium. This domination is not likely to change because South African reserves are sufficient to meet global demand for decades. Recycling of ruthenium is possible and is a potential source of domestic supply.

Samarium

Samarium, a REE, is almost exclusively used in highly specialized SmCo permanent magnets. Such magnets have high thermal stability, high resistance to demagnetization, and good corrosion resistance. SmCo magnets are used in civilian and defense applications and generally cannot easily be substituted with other magnets.

Samarium is mined and concentrated along with the other REEs. Its supply is lower than that of yttrium and the four lighter REEs, cerium, lanthanum, neodymium, and praseodymium. During the separation process, SEG or SEG+ is generally one of the product streams out of the concentrate. Further separation and refining are done to produce samarium oxide. Not all rare earth separation plants produce separated samarium because the extra steps required are costly and technically challenging. China dominates production of separated samarium compounds and metal. The domestic SmCo magnet supply chain requires samarium raw material inputs, which are largely sourced from China, directly or indirectly.

As with the other REEs, current efforts are ongoing to address the foreign reliance on samarium. This includes the efforts by the NDS Program, which has purchased SEG for use in a national emergency.

Strontium

Strontium has a few niche applications, most of which have several substitution options. These applications include natural gas and oil well drilling fluids, permanent ferrite magnets, and aluminum castings alloys. One application where substitution may be challenging is in pyrotechnics, where strontium's addition contributes to increased brilliance and visibility in signal flares and fireworks displays.

The United States does not mine, process, or recycle strontium, although domestic strontium mineral deposits have been identified and operated in the past. Global production of strontium has declined significantly, linked to decreasing demand. Major producers are China, Iran, Mexico, and Spain. The United States imports strontium minerals and compounds predominantly from Mexico.

Tantalum

Tantalum is used in a variety of applications requiring increased chemical, corrosion, and (or) heat resistance. On average, one-half of global tantalum supply is consumed by the electronics industry, primarily to manufacture semiconductors, resistors, and capacitors used in consumer as well as high-performance electronics for the aerospace, automotive, medical, military, and telecommunications industries. Tantalum is also used as an additive in superalloys for aircraft engines and land-based industrial gas turbines and as tantalum carbides in high-speed cutting and boring tools for the mining industry.

Most of the global tantalum mine production is concentrated in Africa, with approximately 40 percent thought to originate in the D.R. Congo. A minor amount of tantalum concentrate is also produced as a byproduct from the tailings of lithium mining operations. Domestic tantalum resources are of low grade, and the United States is currently entirely reliant on foreign sources for its supply of tantalum raw materials. The United States also relies heavily on foreign sources for all other tantalum forms, which include tantalum pentoxide, potassium heptafluorotantalate or "K-salt," tantalum carbide powders, tantalum metal and metal powders, and tantalum waste and scrap. Major tantalum suppliers to the United States include China, Japan, Kazakhstan, Mexico, Rwanda, Thailand, and several European countries. Although several domestic processors can recover tantalum metal from scrap and recycled materials, only one has the capacity to process tantalum concentrates.

Options for improving the domestic supply chain for tantalum include recycling and research into substitution and improved efficiency of use. The NDS holds tantalum carbide powder and tantalum metal ingots.

Tellurium

Tellurium's major use has changed over the past 10 years (2010–19). Previously, it was used mostly as an alloying additive in steel to improve the machining performance of steel. However, it now is used primarily in solar photovoltaic cells, specifically for cadmium telluride cells. Other applications include thermoelectric devices for cooling and energy generation; additives to copper alloys, lead alloys, and cast iron; and in the production of rubber.

In the United States, tellurium is mined with copper and recovered during the refining process; it ends up largely in copper anode slimes. Recovery of tellurium from the slimes has not been commercially viable domestically, and some of it is thought to be exported to be refined to metal outside the United States. Some recycling is thought to occur domestically, but many applications that use tellurium are dissipative; therefore, it is not easily recycled.

Although production data are scant, China is thought to produce more than one-half of the world's refined tellurium, with Japan, Sweden, Russia, and Canada producing most of the rest. The United States imports tellurium largely from Canada, although the reported imported quantities are potentially misleading because they exceed the reported quantity produced in Canada. As with many other minor metals, tellurium supply and demand data are of poor quality and not readily available.

Tin

Tin is commonly used in solders to join metal pieces, especially in electronics and electrical products. Tin plate is a coating applied to steel cans and containers, especially food-grade cans and containers, to prevent corrosion. Tin is also used as an alloying element in such applications as transportation and construction. In most of its end uses, some level of substitution is possible, such as using aluminum or glass instead of metal cans for packaging.

U.S. apparent consumption of tin is met through domestic recycling and imports because no domestic mines or smelters exist. Imports are largely of smelted tin metal, which is available from several countries. Although China produces more than one-half of the world's refined metal, Bolivia, Brazil, Indonesia, Malaysia, and Peru were the sources for most of the refined tin imports to the United States.

Titanium

Titanium mineral concentrates are mined and processed into titanium dioxide and titanium sponge metal. Titanium dioxide is used to produce pigments for paints, coatings, plastics, rubber, paper, and other uses. Titanium dioxide also is used in catalysts, ceramics, and textiles. Although by tonnage, titanium metal accounts for only about 10 percent of titanium mineral concentrate consumption, it is critical to the aerospace industry owing to its high strength-to-weight ratio and corrosion resistance. Titanium metal also is used in steel production for high-strength low-alloy steels and stainless steels.

The United States has the capability to produce titanium in various forms and to recycle titanium scrap. However, although the United States is a net exporter of titanium dioxide and metal ingot, it is highly dependent on imports for titanium mineral concentrates and sponge metal. Moreover, sponge metal production capacity is limited to two domestic facilities and China, Japan, Kazakhstan, Russia, and Ukraine. The collapse of demand for commercial aerospace products in 2020 caused domestic titanium demand to decline and in turn affected domestic producers.

Domestic reserves of titanium minerals are significant, although the size of domestic resources of titanium minerals is not well quantified. Titanium is currently among the metals listed in the Specialty Metals Clause, 252.225-7009 Restriction on Acquisition of Certain Articles Containing Specialty Metals. The NDS holds titanium alloys for national emergency purposes.

Tungsten

Tungsten is used in the aerospace, energy, telecommunications, and defense industries. Tungsten carbide is used in wear-resistant tools, munitions, and oil and gas drilling equipment. When added to superalloys, it is used in jet engines and land-based turbines. Its high melting temperature is important for use in lighting and specialty filaments. It has consistently been identified as a strategic and critical material by the Defense Logistics Agency–Strategic Materials, the manager of the NDS Program.

The United States relies on foreign sources for many of its tungsten forms, including ore and concentrate, ammonium paratungstate (APT), tungsten carbide, tungsten metal powders, and ferrotungsten. Across the tungsten supply chain, China leads global production, accounting for more than one-half of production of each form of tungsten. The United States depends significantly on imports from China to supply its manufacturing base, although imports of various forms of tungsten come from European Union countries, Bolivia, Canada, and Vietnam. Multiple domestic producers make APT from concentrates or scrap; however, only one domestic operation produces ferrotungsten. No tungsten ores or concentrates are produced domestically, although mines have operated in the past. The NDS holds tungsten ores and concentrates, tungsten metal powders, and tungsten-rhenium metal alloy.

Vanadium

Vanadium metal is predominantly used domestically as an alloying element in applications such as turbine blades for jet engines and power generation turbines. Vanadium is also used in batteries for large-scale electricity storage and as an industrial catalyst to produce chemicals. Substitution is possible for some alloys, such as in steel, where manganese, molybdenum, niobium, titanium, and tungsten could potentially replace it. For aerospace titanium alloys, substitution may not be feasible without research and testing.

During the past 10 years, vanadium has been mined sporadically in the United States. The domestic supply chain includes processing and recycling of vanadium, sometimes from imported materials, for which quantitative data are lacking. Many forms of vanadium are traded globally, but about one-half of the imports to the United States are in the form of ferrovanadium and vanadium pentoxide, both of which are sourced from a several countries, including Austria, Brazil, China, Russia, and South Africa. China and Russia are the world's leading producers of mined vanadium, together accounting for more than 80 percent of the world's mined vanadium.

Yttrium

Yttrium is mostly used in ceramics and is critical for high temperature applications such as thermal barrier coatings on turbines and as an ion conductor in solid oxide fuel cells. In ceramic form, it is also used in structural and cutting tool applications, oxygen sensors, and fiber optic connectors. In metal form, its main application is for nonferrous alloys for the aerospace, automotive, and defense industries. Along with several other heavy REEs, yttrium is used in phosphors for lighting.

The domestic supply chain is entirely reliant on foreign supplies of raw materials, with most of the world's production concentrated in China. Addressing this supply risk requires a complex, long-term strategy, which is ongoing. Although the United States had no domestic supply of yttrium 10 years ago (2010), research has progressed, and several potential domestic reserves for REEs may provide options for the domestic supply chain in the future.

Zinc

Zinc has a broad range of uses in metal and compound form and is the fourth most globally produced metal mineral commodity in terms of annual tonnages. By tonnage, one of the most important applications for zinc is as a corrosion protection coating for steel (galvanization), which is used in motor vehicles and other steel applications. Other metal uses for zinc include alloying to make bronze and brass and in zinc-based castings and rolled products. These are then used in hardware (such as bathroom and other home fixtures), machinery, jewelry, and toys. In compounds, zinc is used in pharmaceuticals, in paint, in the agricultural industry, to make rubber, and in other chemical applications.

Multiple mines in the United States extract zinc ore; however, only two smelters process and refine zinc to produce commercial-grade metal. The United States is a net exporter of zinc ores and concentrates, but a large net importer of refined zinc. Most of the imports of refined zinc are from Canada and Mexico. Many countries mine and refine zinc, although some only mine or refine it. Countries with integrated zinc industries are Australia, Canada, China, India, Mexico, Peru, and Russia.

Zirconium and Hafnium

Zirconium is crucial to nuclear fuel technologies as nuclear fuel cladding. Zirconium metal also is used in nonnuclear applications in corrosive environments in the chemical-processing industry. Hafnium is used in superalloys, especially for aeronautic applications, as well as high-temperature ceramics and nuclear control rods.

Zirconium and hafnium are often produced together because hafnium occurs in zircon, a zirconium mineral. Zirconium-bearing sand is commonly reduced and fused into fused zirconia. Fused zirconia is turned into hafnium-containing zirconium tetrachloride through a high temperature reaction with carbon black and chlorine. For nonnuclear applications, zirconium metal containing small quantities of hafnium may be used; commercial-grade zirconium sponge contains hafnium. However, for nuclear fuel cladding, zirconium metal must be free of hafnium. In order to obtain nuclear-grade zirconium metal, zirconium and hafnium must be separated to produce zirconium sponge metal and hafnium.

Only a few countries produce zirconium metal. Even fewer produce nuclear-grade zirconium metal, and those countries also produce hafnium. Two companies in the United States produce zirconium and hafnium metal. Theoretically, some recycling is possible, but it is not reported. The United States does not import much zirconium metal, and China is the top import source for zirconium metal. China and France are the top import sources for hafnium, although United States trade data on hafnium is potentially problematic, partly owing to a lack of reported export data. Moreover, reliable data on the precursors to zirconium metal, fused zirconia, and zirconium oxychloride is lacking. Reliable data would be necessary to better assess these materials; however, both materials are part of very small markets where such information is tightly guarded.

References Cited

Nassar, N.T., 2015, Global stocks and flows, losses, and recoveries of platinum-group elements: Yale University, PhD dissertation.

U.S. Census Bureau, 2020, USA Trade Online, accessed October 1, 2020, at https://usatrade.census.gov/.

U.S. Geological Survey, 2020a, Minerals yearbook: Reston, VA, U.S. Geological Survey. [Also available at https://www.usgs.gov/centers/nmic/minerals-yearbook-metals-and-minerals.]

U.S. Geological Survey, 2020b, Mineral commodity summaries 2020: Reston, VA, U.S. Geological Survey, 204 p. [Also available at http://pubs.er.usgs.gov/publication/mcs2020.]

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