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Draft Critical Mineral List—Summary of Methodology and Background Information—U.S. Geological Survey Technical Input Document in Response to Secretarial Order No. 3359

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

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By Steven M. Fortier, Nedal T. Nassar, Graham W. Lederer, Jamie Brainard, Joseph Gambogi, Erin A. McCullough

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

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Statement of Issue

Pursuant to the Presidential Executive Order (EO) No. 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals," the Secretary of the Interior, in coordination with the Secretary of Defense, and in consultation with the heads of other relevant executive departments and agencies, was tasked with developing and submitting a draft list of minerals defined as "critical minerals" to the Federal Register within 60 days of the issue of the EO (December 20, 2017; Executive Office of the President, 2017). U.S. Department of the Interior (DOI) Secretarial Order (SO) No. 3359, "Critical Mineral Independence and Security," tasked the Director of the U.S. Geological Survey (USGS), in coordination with the Bureau of Land Management (BLM), with developing and submitting a proposed draft list of minerals defined as "critical minerals" within 30 days of the issue of the SO (U.S. Department of the Interior, 2017). USGS and BLM developed the unranked draft list presented herein in cooperation with the U.S. Departments of Defense (DOD), Energy, State, and Commerce, and other members of the National Science and Technology Council Subcommittee on Critical and Strategic Mineral Supply Chains (CSMSC).

Summary of the Proposed Draft List

Based on an analysis using multiple criteria explained below, 35 minerals or mineral material groups have been identified that are currently (February 2018) considered critical. These include the following: aluminum (bauxite), antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, graphite (natural), hafnium, helium, indium, lithium, magnesium, manganese, niobium, platinum group metals, potash, rare earth elements group, rhenium, rubidium, scandium, strontium, tantalum, tellurium, tin, titanium, tungsten, uranium, vanadium, and zirconium. The categorization of minerals as critical may change during the course of the review process and is thus provisional.

Definition

A "critical mineral," as defined by EO No. 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. Disruptions in supply chains may arise for any number of reasons, including natural disasters, labor strife, trade disputes, resource nationalism, conflict, and so on. The draft list provided herein is based on the definition of a "critical material" provided in the EO. The U.S. Government and other organizations have other definitions and rely on other criteria to identify a material or mineral as "critical" or otherwise important. This draft list is not intended to replace related terms and definitions of materials that are deemed strategic, critical, or otherwise important (for example, the National Defense Stockpile).

Introduction

Lists of critical minerals, although useful to identify and prioritize materials of concern, are, by necessity, a simplification of a complex issue; there is no one method that will meet the needs of all interested parties. A number of factors are relevant when using such information. First, what constitutes a critical mineral depends, in some respects, on who is asking the question. A company producing hydrocarbons, for example, may have a very different idea of what materials are critical than an electronics manufacturer or the DOD. The USGS tracks nonfuel mineral information on a continuous and annual basis, in part, to monitor the criticality and import dependence of critical minerals. The U.S. Energy Information Administration tracks uranium mineral information in a similar way. The USGS also completes geologic mapping, mineral resource assessments, and basic research that allow the distribution of critical minerals to be identified and understood. Without this background information, it is not possible to fully understand the criticality and security of the Nation's mineral supply. Specifically, various agencies, including the DOI, DOD, U.S. Department of Commerce, U.S. Department of Energy, U.S. Department of Agriculture, and the United States Trade Representative, would be expected to prioritize specific minerals in the draft list presented herein differently based on the importance to their missions.

Previous work in this field has resulted in several methodologies and produced a variety of lists of critical minerals particularly during the decade after the seminal work of the National Academy of Sciences in 2008 (National Research Council, 2008). All such studies differed somewhat in the approach taken and the resulting lists that were produced; a review of these studies is beyond the scope of this document. For the purposes of meeting the objectives of the above referenced EO and SO, the approach described in the next paragraph was used to generate the draft list proposed herein.

The critical mineral early warning screening methodology developed by the CSMSC in 2016 (U.S. National Science and Technology Council, 2016), and updated in 2017 (McCullough and Nassar, 2017), served as the starting point for the development of the draft list. The screening methodology was designed to identify and prioritize minerals or mineral materials for in depth study to evaluate risks to security of supply. The screening methodology is global in scope and did not specifically address U.S. import reliance. It only addressed nonfuel minerals and, thus, did not include uranium. One of the principle metrics used in the CSMSC screening methodology was the Herfindahl-Hirschman index (HHI). The HHI is used by the Department of Justice and the Federal Trade Commission to identify highly concentrated markets when a company may control market share above an established threshold of 2,500 on a dimensionless scale that ranges from 0 to 10,000. Additional tools and sources of information used to produce the draft list, make it U.S. specific, and that include consideration of uranium were as follows: (1) U.S. net import reliance (NIR) statistics as published annually in the USGS Mineral Commodity Summaries (U.S. Geological Survey, variously dated); (2) USGS Professional Paper 1802 "Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply" (Schulz and others, 2017); (3) various inputs from the DOD; (4) the National Defense Authorization Act for fiscal year 2018 (H.R. 2810); (5) U.S. Energy Information Administration uranium statistics in the "2016 Uranium Marketing Annual Report" (U.S. Energy Information Administration, 2017); and (6) the judgment of subject-matter experts of the USGS, and other U.S. Government agencies including representatives of other DOI Bureaus and members of the CSMSC Subcommittee. Additional information and references on these tools and sources are provided in appendix 1.

The draft list resulting from the application of these metrics is shown in table 1 with materials listed in alphabetical order. Most of entries in the table are materials for which production concentration and net import reliance are high (typically HHI greater than 2,500 and NIR greater than 50 percent for either the years 2016, 2017, or both). Entries that are below the chosen threshold based on one metric or the other, but for which a case for inclusion can be made on grounds of particularly critical applications, also are included. The latter is based on the judgment of subject-matter experts of the CSMSC Subcommittee. The countries that are the largest producers and largest U.S. suppliers are listed adjacent to the respective metrics for those categories. As an example, China dominates the production of antimony and is the largest import source to the United States. It should be noted that import reliance is not the same as import vulnerability (defined as a material with high NIR that is sourced from a country or countries with high governance risk). Many of the countries identified as the largest source of U.S. imports also have relatively high governance risks. Key end use sector data also are shown in a matrix format indicative of the industrial sectors in which a particular material finds important end uses. Finally, notable examples of end use applications are given for each listed material. A more detailed view of the industrial sectors and key technologies for which the listed commodities find important end uses is provided in table 2. A brief summary of information relevant to the criticality for each listed material is included in appendix 2.

A supply chain approach was used for some of the materials on the draft list, consistent with the definition of a critical mineral in the EO. For example, aluminum is included to represent the aluminum supply chain because the United States is 100 percent reliant on imports of metallurgical grade bauxite, and some forms of high purity alumina and aluminum metal used for important applications also are considered critical. Likewise, several important ferroalloys used to manufacture specialty steels and superalloys are not listed individually; instead, they are included by inference in the supply chain of the material alloyed with iron. Ferroniobium, for example, is captured by the presence of niobium on the draft list in recognition that niobium is part of the ferroniobium supply chain. It should be noted that potential supply chain vulnerabilities relating to critical minerals extend beyond what is described herein and should be considered as part of the strategy within the report to the President required by the EO. For example, enhancing domestic mineral processing capability is important to prevent the immediate export of domestically mined ore.

Table 1. Draft list of critical minerals.

[X, applicable sector; --, not applicable]

Mineral commodity	Sectors: Aerospace (nondefense)	Defense	Energy	Telecommunications and electronics	Transportation (nonaerospace)	Other	Top producer	Top supplier	Notable example application
Aluminum	X	X	X	X	X	X	China	Canada	Aircraft, power transmission lines, lightweight alloys.
Antimony	--	X	X	X	X	X	China	China	Lead-acid batteries.
Arsenic	--	X	X	X	--	X	China	China	Microwave communications (gallium arsenide).
Barite	--	--	X	X	--	X	China	China	Oil and gas drilling fluid.
Beryllium	X	X	X	X	--	X	United States	Kazakhstan	Satellite communications, beryllium metal for aerospace.
Bismuth	--	X	X	X	--	X	China	China	Pharmaceuticals, lead-free solders.
Cesium and rubidium	X	X	X	X	--	X	Canada	Canada	Medical applications, global positioning satellites, night-vision devices.
Chromium	X	X	X	X	X	X	South Africa	South Africa	Jet engines (superalloys), stainless steels.
Cobalt	X	X	X	X	X	X	Congo[1] (Kinshasa)	Norway	Jet engines (superalloys), rechargeable batteries.
Fluorspar	--	--	X	X	--	X	China	Mexico	Aluminum and steel production, uranium processing.
Gallium	X	X	X	X	--	X	China	China	Radar, light-emitting diodes (LEDs), cellular phones.
Germanium	X	X	X	X	--	X	China	China	Infrared devices, fiber optics.
Graphite (natural)	X	X	X	X	X	X	China	China	Rechargeable batteries, body armor.
Helium	--	--	--	X	--	X	United States	Qatar	Cryogenic (magnetic resonance imaging [MRI]).
Indium	X	X	X	X	--	X	China	Canada	Flat-panel displays (indium-tin-oxide), specialty alloys.
Lithium	X	X	X	X	X	X	Australia	Chile	Rechargeable batteries, aluminum-lithium alloys for aerospace.
Magnesium	X	X	X	X	X	X	China	China	Incendiary countermeasures for aerospace.
Manganese	X	X	X	X	X	X	China	South Africa	Aluminum and steel production, lightweight alloys.
Niobium	X	X	X	X	--	X	Brazil	Brazil	High-strength steel for defense and infrastructure.
Platinum group metals[2]	X	--	X	X	X	X	South Africa	South Africa	Catalysts, superalloys for jet engines.
Potash	--	--	X	X	--	X	Canada	Canada	Agricultural fertilizer.
Rare earth elements[3]	X	X	X	X	X	X	China	China	Aerospace guidance, lasers, fiber optics.
Rhenium	X	--	X	X	--	X	Chile	Chile	Jet engines (superalloys), catalysts.
Scandium	X	X	X	X	--	X	China	China	Lightweight alloys, fuel cells.
Strontium	X	X	X	X	X	X	Spain	Mexico	Aluminum alloys, permanent magnets, flares.
Tantalum	X	X	X	X	--	X	Rwanda	China	Capacitors in cellular phones, jet engines (superalloys).
Tellurium	--	X	X	X	--	X	China	Canada	Infrared devices (night vision), solar cells.
Tin	--	X	--	X	--	X	China	Peru	Solder, flat-panel displays (indium-tin-oxide).
Titanium	X	X	X	X	--	X	China	South Africa	Jet engines (superalloys) and airframes (titanium alloys), armor.
Tungsten	X	X	X	X	--	X	China	China	Cutting and drilling tools, catalysts, jet engines (superalloys).
Uranium	X	X	X	--	--	X	Kazakhstan	Canada	Nuclear applications, medical applications.
Vanadium	X	X	X	X	--	X	China	South Africa	Jet engines (superalloys) and airframes (titanium alloys), high-strength steel.
Zirconium and hafnium	X	X	X	X	--	X	Australia	China	Thermal barrier coating in jet engines, nuclear applications.

[1]Democratic Republic of the Congo.

[2]This category includes platinum, palladium, rhodium, ruthenium, iridium, and osmium.

[3]This category includes yttrium and the lanthanides.

Table 2. Important technologies and applications by mineral commodity and industrial sector.

[NA, not applicable; SOFC, solid oxide fuel cell; PEM, polymer electrolyte membrance]

Mineral commodity	Aerospace (nondefense)	Defense	Energy	Telecommunications and electronics	Transportation (nonaerospace)	Other
Aluminum	• Airframes • Fuselage	• Aerospace • Naval vessels • Ground vehicles	• Power transmission lines • Lightweight alloys • Land based turbines (superalloys, coating) • Aluminum oxide catalyst supports	NA	• Marine vessels • Ground vehicles • Lightweight alloys	• Infrastructure • Packaging • Aluminum oxide refractories
Antimony	NA	• Lead-acid batteries • Infrared devices (night vision)	• Lead-acid batteries	• Semiconductors	• Lead-acid batteries	• Flame-retardant materials • Glass and ceramics manufacturing • Plastics manufacturing
Arsenic	NA	• Semiconductors	• Solar cells	• Cellular phones	NA	• Gallium arsenide integrated circuits • Optoelectronic devices
Barite	NA	NA	• Oil and gas drilling fluid	NA	NA	• Radiation shielding • Medical applications
Beryllium	• Structural and optical components • Aluminum alloys	• Guidance systems • Radar	• Oil and gas drilling equipment • Nuclear applications	• Undersea cable housings • Contacts	NA	• X-ray windows
Bismuth	NA	• Thermoelectric devices • Machining alloys	• Bismuth oxide sofc applications	• Solder • Semiconductor manufacturing	NA	• Pharmaceutical • Glass and ceramics manufacturing • Metallurgical applications
Cesium and rubidium	• Global positioning satellites • Guidance systems	• Infrared devices (night vision)	• Fuel cells • Solar cells	• Cellular phones • Motion sensor devices • Fiber optics • Photoelectric cells	NA	• Medical applications • Scintillation • Atomic clocks • Specialty glass
Chromium	• Jet engines (superalloys)	• Superalloys • Specialty steels	• Land-based turbines • SOFC applications	NA	NA	• Stainless steel • Specialty steels • Corrosion resistance
Cobalt	• Jet engines (superalloys) • Rechargeable batteries	• Superalloys • Permanent magnets • Rechargeable batteries	• Rechargeable batteries • Petroleum catalysts • Land-based turbines • Superalloys •SOFC catalysts • High temperature boiler tubing	• Rechargeable batteries	• Rechargeable batteries	• Cemented carbides • Specialty steels

Table 2. Important technologies and applications by mineral commodity and industrial sector.—Continued

[NA, not applicable; SOFC, solid oxide fuel cell; PEM, polymer electrolyte membrance]

Mineral commodity	Aerospace (nondefense)	Defense	Energy	Telecommunications and electronics	Transportation (nonaerospace)	Other
Fluorspar	NA	NA	• Uranium processing	• Semiconductor manufacturing	NA	• Hydrofluoric acid • Steelmaking • Aluminum production • Metallurgical applications • Fluorochemicals
Gallium	• Solar cells in satellites • Microwave power transistors	• Radar • Radio frequency amplifiers • Infrared imaging	• Solar cells • Light-emitting diodes	• Cellular phones • Light-emitting diodes • Integrated circuits	NA	• Optoelectronic devices • Lasers • Photodetectors
Germanium	• Solar cells in satellites	• Infrared devices (night-vision) • Guidance systems	• Solar cells	• Fiber optics • Integrated circuits	NA	• Optoelectronic devices • Polymer manufacturing
Graphite	• Rechargeable batteries • Jet engine components	• Munitions • Rechargeable batteries • Body armor • Superalloy components	• Rechargeable batteries • Nuclear applications • PEM fuel cell applications • Land based turbines	• Rechargeable batteries	• Rechargeable batteries	• Lubricant • Refractories • Electrodes • Steelmaking
Helium	NA	NA	NA	• Semiconductor manufacturing	NA	• Magnetic resonance imaging • Cryogenic cooling • Shielding gas • Tank purging • Leak detection
Indium	• Aircraft wind shield	• Infrared imaging	• Solar cells • Alkaline batteries • Nuclear applications • Light-emitting diodes	• Fiber optics • Flat-panel displays • Light-emitting diodes • Semiconductors • Thermal interface materials	NA	• Lasers • Solder
Lithium	• Rechargeable batteries • Aluminum alloys (structural)	• Rechargeable batteries • Aerospace alloys • Tritium production support	• Rechargeable batteries • Cooling water chemistry in nuclear power reactors	• Rechargeable batteries	• Rechargeable batteries	• Glass and ceramics manufacturing • Lubricant • Medical applications
Magnesium	• Aluminum alloys	• Incendiaries • Munitions • Aluminum alloys • Radar	• Lightweight alloys	NA	• Automobile components	• Metallurgical applications • Corrosion resistance

Table 2. Important technologies and applications by mineral commodity and industrial sector.—Continued

[NA, not applicable; SOFC, solid oxide fuel cell; PEM, polymer electrolyte membrance]

Mineral commodity	Aerospace (nondefense)	Defense	Energy	Telecommunications and electronics	Transportation (nonaerospace)	Other
Manganese	• Jet engines (superalloys) • Aluminum alloys	• Aluminum alloys	• Land-based turbines • Lightweight alloys • Rechargeable batteries	NA	• Aluminum alloys	• Specialty steel
Niobium	• Jet engines (superalloys)	• Jet engines (superalloys) • Specialty steels	• Land-based turbines • Oil and gas pipelines (specialty steel) • SOFC catalysts Nickel based superalloys	NA	NA	• Superconducting alloys
Platinum-group metals	• Jet engines (casting, coatings)	NA	• Petroleum catalysts • Land-based turbines • Fuel cells • Autocatalysts	• Hard-disk drives • Capacitors • Flat-panel displays	• Autocatalysts • Fuel cells • Automotive components	• Chemical catalysts • Medical applications • Refractory crucibles • Metallurgical applications • Integrated circuits
Potash	NA	NA	• Oil and gas drilling fluid	NA	NA	• Agricultural fertilizer
Rare earth elements	• Jet engines (ceramics, superalloys)	• Guidance systems • Lasers • Radar • Sonar	• Petroleum catalysts • Permanent magnets for electric motor and wind turbines • Fuel additives • Wind turbines • Nuclear applications • Rechargeable batteries • SOFC applications • Turbines (superalloys, coating)	• Fiber optics • Signal amplifiers • Cellular phones • Flat-panel displays • Hard-disk drives • Lighting • Electric motors • Sensors	• Autocatalysts • Electric motor magnets • Automotive glass	• Steel and nonferrous alloys • Chemical catalysts • Ceramics • Permanent magnets • Polishing compounds • Lasers • Optical glass • Medical imaging • X-ray scintillometers
Rhenium	• Jet engines (superalloys)	NA	• Petroleum catalysts • Land-based turbines	• High-temperature applications	NA	• Refractory crucibles
Scandium	• Aluminum-scandium alloys	• Aluminum alloys • Lasers	• Fuel cells • Lighting • Petroleum refining	• Lasers • Lighting • Phosphors • Piezoelectrics	• Fuel cells	• Catalysts • Ceramics • Flares and pyrotechnics
Strontium	• Aluminum alloys • Superalloys	• Flares, tracer ammunition	• Oil and gas drilling • Permanent magnets	• Permanent magnets • Semiconductors	• Permanent magnets • Aluminum alloys	• Ceramics • Metal refining • Flares and pyrotechnics

Table 2. Important technologies and applications by mineral commodity and industrial sector.—Continued

[NA, not applicable; SOFC, solid oxide fuel cell; PEM, polymer electrolyte membrance]

Mineral commodity	Aerospace (nondefense)	Defense	Energy	Telecommunications and electronics	Transportation (nonaerospace)	Other
Tantalum	• Jet engines (superalloys)	• Armor-piercing munitions • Aircraft components	• Land-based turbines	• Capacitors • Cellular phones • Semiconductors • Flat-panel displays	NA	• Cemented carbides • Chemical processing equipment • Corrosion resistance • Medical devices
Tellurium	NA	• Infrared devices (night-vision) • Temperature control systems	• Solar cells	• Photoreceptor devices • Semiconductors	NA	• Specialty steels • Nonferrous alloys • Thermoelectric applications
Tin	NA	• Nonferrous alloys (bearings)	NA	• Solder • Flat-panel displays	NA	• Solder • Packaging • Polymer manufacturing • Catalysts • Glass manufacturing
Titanium	• Jet engines (superalloys) • Airframes	• Aerospace • Ground vehicle armor • Artillery • Corrosion resistance	• Oil and gas drilling equipment • Corrosion resistance • Land based turbines	NA	NA	• Medical devices • Photocatalysts
Tungsten	• Jet engines (superalloys)	• Armor-piercing munitions	• Oil and gas drilling equipment • Land-based turbines • Petroleum catalysts	• Cellular phones • Contacts • Filaments • Lighting	NA	• Cemented carbides • Specialty steels • Chemical catalysts • Corrosion resistance
Uranium	• Space missions	• Nuclear applications • Support for tritium production • Naval propulsion	•Electricity production, including supporting manufacturing	NA	NA	• Medical isotope production and development
Vanadium	• Jet engines (superalloys) • Titanium alloys	• Specialty steel • Titanium alloys • Land based turbines	• Petroleum catalysts • Grid scale batteries	NA	NA	• Chemical catalysts • Specialty steel • Titanium alloys
Zirconium and hafnium	• Jet engines (ceramics, superalloys)	• Incendiaries	• Nuclear applications • SOFC applications • Land based turbines (coating)	NA	NA	• Corrosion resistance • Technical ceramics • Chemical catalysts

Another simplification used is categorization into mineral groups. Rare earth elements, for example, include yttrium and all the lanthanides. All these elements are typically present together in mineral deposits and, thus, share the same high levels of HHI and NIR. Scandium, which is often included with yttrium and the lanthanides under rare earth elements, behaves differently in natural systems and is not necessarily always present together with the other rare earths, so it is listed separately. The platinum group elements include platinum, palladium, rhodium, ruthenium, and iridium. Hafnium is produced solely as a byproduct of zirconium processing, so the two are combined on the draft list.

Notably, several materials on the draft list are recovered only as byproducts of other more-common mineral commodities. These ubiquitous materials may not meet the criteria to be included on the draft list. Tellurium, for example, is a byproduct of copper refining. Rhenium is a byproduct of molybdenum processing. Despite these codependencies, neither copper nor molybdenum is designated as critical. Other major mineral commodities such as gold, lead, zinc, nickel, and iron also are important potential sources for byproduct critical mineral production. A strategy for addressing the special characteristics of byproduct mineral supply needs to be an important part of the report submitted on implementation of the EO. Additional discussion of byproduct mineral commodities is included in appendix 1.

There are many mineral materials not included on the draft critical minerals list that are still of substantial importance to the U.S. economy. These materials are not considered critical in the conventional sense because the United States largely meets its needs for these through domestic mining and processing; thus, a substantial supply disruption is considered unlikely. Industrial minerals, for example, are the materials that form the physical basis for much of our Nation's infrastructure. These include materials for making cement (limestone, clays, shales, and aggregates); materials (such as iron and steel) used in rebar, steel mesh, and wire grids to reinforce concrete structures; and materials on which to place infrastructure, such as base courses composed of crushed stone and aggregates. These construction commodities are the largest (by volume) sectors of the U.S. mineral industries. Other important mineral materials include inputs into the chemical industries or agricultural sector including sulfur, salt, phosphate, and gypsum. The manufacturing of products such as glass, ceramics, refractories, and abrasives require quartz, soda ash, feldspar, kaolin, ball clays, mullite, kyanite, industrial diamonds, garnets, corundum, and borates. Many others could be listed.

Finally, it should be noted that mineral criticality is not static, but rather changes over time. This analysis represents a snapshot in time that should be reviewed and updated periodically using the most recently available data to accurately capture rapidly evolving technological developments and the consequent material demands.

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Appendix 1. Criticality Methodology and Other Considerations

National Science and Technology Council Critical Mineral Early Warning Screening Methodology

The National Science and Technology Council Critical Mineral Early Warning Screening Methodology (U.S. National Science and Technology Council, 2016; McCullough and Nassar, 2017) applies a country-agnostic view when screening 77 nonfuel mineral commodities. The methodology consists of two stages, starting with an indicator-based approach that then informs deep-dive studies completed in the second stage. The three fundamental indicators used in the first stage are supply risk (*R*); production growth (*G*); and market dynamics (*M*). Each indicator aims to capture a different yet complementary aspect of criticality: *R* attempts to capture the risk associated with the concentration of production in countries with low governance, *G* evaluates the growth of world production to highlight a commodity's growing importance, and *M* examines price volatility to capture the stability of the commodity's market. The outputs provided by each indicator are normalized on a common scale from 0 to 1 in which higher values indicate a relatively higher degree of criticality. This scale gives each indicator an equal weight before being combined into a criticality potential score (*C*) through a geometric mean. Each indicator is applied consistently to every screened commodity on an annual basis. Data are primarily sourced from the U.S. Geological Survey. The minerals identified in the first stage as having a statistically significant high *C* score then undergo "deep-dive" studies in the second stage designed to closely evaluate circumstances specific to each commodity.

Production Concentration

The mining and processing of many nonfuel mineral commodities has become increasingly concentrated in only a few nations (for example, Chinese refining of cobalt). This trend reflects changes in global demand for materials, comparative advantages in production (aluminum production from low-cost energy in United Arab Emirates), or government policies to secure domestic supplies of strategic materials (beryllium in the United States), whereas historic production concentrations typically have reflected geological distributions (platinum-group metals in South Africa). Highly concentrated production is an important component of criticality for geologically derived materials. Mineral production that is concentrated in a small number of countries poses a higher risk of triggering a supply disruption than a mineral with widely dispersed production. Highly consolidated supply chains have an increased risk of supply disruption from foreign government action, trade disputes, civil unrest, natural disasters, and other hazards. Production concentration was quantified using a metric of market concentration known as the Herfindahl-Hirschman Index (HHI), which is calculated as the sum of the squares of each producing nation's global production share of a commodity in a given year. HHI is used by the Department of Justice and the Federal Trade Commission to identify highly concentrated markets where firms exhibit elevated control above an established threshold of 2,500 on a scale that ranges from 0 to 10,000. Similarly, a threshold of 2,500 was used to identify commodities with highly concentrated production, and the largest producer of each mineral commodity was indicated.

United States Net Import Reliance

The United States relies on imports of many mineral commodities because domestic production is either lacking or insufficient to satisfy domestic demand by consumers. As a metric of this foreign dependency, net import reliance (NIR) is calculated as the amount of imported material (including changes in stockpiles) minus exports and changes in government and industry stocks and is expressed as a percentage of domestic consumption (U.S. Geological Survey, 2017). For example, a mineral commodity that is not produced in the United States has an NIR of 100 percent. When U.S. production of a mineral commodity exceeds domestic consumption, the United States is a net exporter. For this analysis, materials that require imports to satisfy more than one-half of domestic consumption are deemed to have a high U.S. NIR. The largest foreign suppliers of these targeted mineral commodities have been included in addition to the NIR to provide broader strategic context, which highlights that not only does the United States require foreign supplies, but that 12 out of the 26 commodities with high United States NIR are sourced primarily from China. However, high NIR should not be construed to always pose a potential supply risk. For example, three of the commodities deemed critical or near critical are primarily imported from Canada, a nation that is integrated with the United States defense industrial base.

Byproduct Commodities

Many commodities are not mined directly, but are instead recovered during the processing, smelting, or refining of a host material and are, therefore, deemed "byproducts" (fig. 1.1). These byproducts are typically chemically similar to their host material and are present in the same ores, albeit at a small fraction of the concentration (for example, tellurium in copper ores). Byproducts are almost never independently economically viable to mine, thus relying on the economics of the host material being mined, which may then yield an economically recoverable concentration of the byproduct in slag, ash, flue gasses, or other “waste” streams. The recovery of these byproducts typically is low compared to the total amount of material that was made available from mining, and recovery facility capacity poses a greater restriction on supply than geologic availability. Of the 30 commodities deemed herein as critical or near critical, 12 are byproducts, including helium, which is recovered from oil and gas extraction. Therefore, strategies to increase the domestic supply of these commodities also should consider the mining and processing of the host materials because enhanced recovery of byproducts alone may be insufficient to meet U.S. consumption.

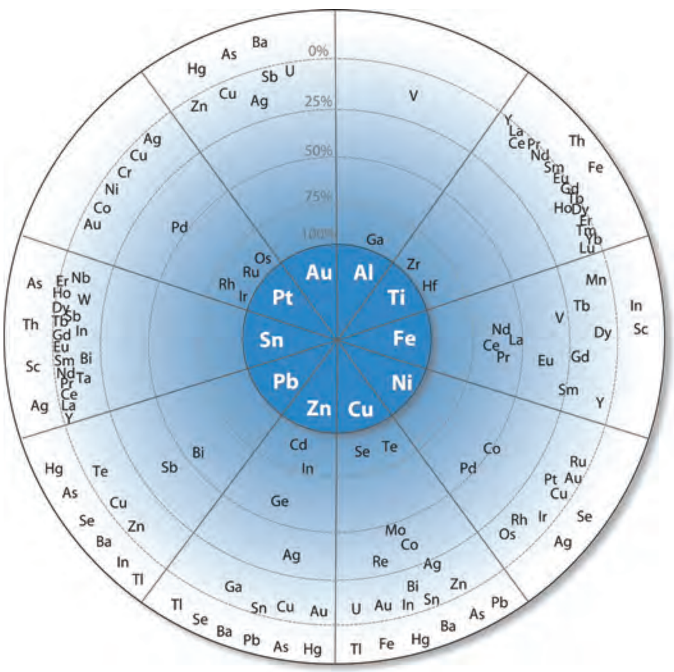

Figure 1.1. Relation between byproducts and host materials (from Nassar and others, 2015). The principal host metals form the inner circle. Byproduct elements are in the outer circle at distances proportional to the percentage of their primary production (from 100 to 0 percent) that originates with the host metal indicated.

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Appendix 2. Brief Commodity Summaries—Critical Minerals

Table 2.1. Critical mineral commodity summaries.

[Commodities are listed alphabetically. Supply chain considerations were utilized in the selection process, meaning a commodity is included if any step in its supply chain is deemed problematic. Information in this table is from U.S. Geological Survey (2017, 2018, variously dated)]

Mineral commodity	Summary
Aluminum	Historically, the United States has had a low import reliance on aluminum metal, although this has been changing in recent years because of the loss of domestic smelting capacity; moreover, production of aluminum has become increasingly concentrated in China in recent years. The larger concern for aluminum is, however, the bauxite ore, on which the United States is highly import reliant, which is used to produce alumina (the feedstock for primary aluminum smelters). Bauxite is imported from tropical regions, dominantly Jamaica, as well as Brazil, Guinea, and Guyana. Alumina imports from Australia and Brazil are important sources for specific aluminum smelters, although these imports generally are offset by alumina exports.
Antimony	Antimony is not mined domestically. The United States produces primary antimony metal and oxide from imported feedstocks and secondary (recycled) antimony from antimonial lead recovered from spent lead-acid batteries. Alloys of antimony and lead provide enhanced electrical properties to batteries. In addition to its use in antimonial lead for lead-acid batteries, other major uses are flame-retardants, lead alloys, as a catalyst for plastics, polyvinyl chloride stabilizers, ceramics, and glass.
Arsenic	Despite an abundance of domestic resources, primary arsenic metal has not been produced in the United States in decades. Arsenic is used mostly as arsenic trioxide for the generation of chromated copper arsenide for pressure-treating lumber. However, arsenic, as a metal, also has uses as a hardener for lead alloys and in gallium arsenide semiconductors. The United States is reliant entirely on imports, largely from China and Morocco. Currently (February 2018), arsenic is not recovered from end-of-life electronics. Manufacturers, however, recycle new scrap.
Barite	Barite is used overwhelmingly in the oil and gas industry as a high-density component of drilling mud, and consumption mirrors the activity of the petroleum industry. The United States is highly reliant on barite imports, largely from China, and additional concerns address the supply of high-specific-gravity material required by the petroleum industry. Recent exploration of domestic barite resources has been limited, although significant resources have been identified.
Beryllium	The United States produces about 85 percent of global beryllium mine production from one deposit in Utah, and the remainder is produced in China and other countries. Only three countries process beryllium ores into beryllium products: China, Kazakhstan, and the United States. Most beryllium is used to make beryllium-copper and other alloys, whereas 20 percent of consumption is in the form of beryllium metal, composites, and oxides. Beryllium alloys are used widely in telecommunications, electrical components, electronics, and many other products. Beryllium metal is used mainly in defense, aerospace, and nuclear applications. The Defense Logistics Agency maintains an inventory of beryllium metal in the National Defense Stockpile. The only domestic beryllium metal processing facility was constructed under Title III of the Defense Production Act and began operation in 2012.
Bismuth	Aside from small quantities of bismuth recycled from old and new scrap, all bismuth consumption in the United States is imported, mainly from China, which is the world's largest producer. Bismuth is contained in some of the lead ores mined domestically, but all lead concentrate is exported for smelting since the closure of the last primary lead smelter in 2013. Bismuth has major applications in chemicals for cosmetic, industrial, laboratory, and pharmaceutical uses. Bismuth also is used in a number of metallurgical applications, including use as a nontoxic replacement for lead. Bismuth can be replaced in many of its major applications.
Cesium and rubidium	The United States relies on imports for cesium and rubidium. Only a few thousand kilograms of cesium and rubidium are consumed in the United States every year. By gross weight, cesium formate brines used for high-pressure, high-temperature well drilling for oil and gas production and exploration are the primary applications for cesium. Rubidium is used in specialty glass and night-vision devices. The United States sourced most of its pollucite, the principal mineral source of cesium, from the largest known deposit in North America at Bernic Lake, Manitoba, Canada; however, that operation ceased mining at the end of 2015 but continued to produce cesium products from stocks. The company indicated it had sufficient stocks of raw materials to continue producing its cesium products for the near future. Rubidium concentrate is produced as a byproduct of pollucite (cesium) and lepidolite (lithium) mining and is imported from other countries for processing in the United States.

Table 2.1. Critical mineral commodity summaries.—Continued

[Commodities are listed alphabetically. Supply chain considerations were utilized in the selection process, meaning a commodity is included if any step in its supply chain is deemed problematic. Information in this table is from U.S. Geological Survey (2017, 2018, variously dated)]

Mineral commodity	Summary
Chromium	Chromium is used predominantly in the production of stainless steel and superalloys where it adds temperature and corrosion resistance. U.S. chromite reserves are small, with no mining, resulting in chromium-bearing materials being produced from imported chromite ores and ferrochromium. Globally, South Africa has the largest chromite reserves and is the leading source of chromium-bearing imports. Limited substitutes exist for chromium in alloy applications; however, recycling is extensive, accounting for about 40 percent of consumption.
Cobalt	Congo (Kinshasa) is increasingly becoming a dominant miner of cobalt, with more than one-half of world production in 2016. This production was mainly a byproduct of copper operations. Cobalt also is recovered as a byproduct of nickel mining in Russia and other countries. Like the United States, China lacks sufficient domestic supplies for its industries and, thus, has aggressively sought to secure its supplies through overseas acquisitions. Cobalt demand is expected to grow significantly because of its use in rechargeable batteries for electric vehicles and other technologies. Other uses of cobalt are in superalloys for jet engines and cemented carbides for cutting tools and wear-resistant applications.
Fluorspar	The United States is highly import reliant on foreign sources of fluorspar, chiefly Mexico, with limited domestic production. Fluorspar's uses typically are categorized into three broad categories: in the production of hydrofluoric acid, in the production of aluminum fluoride (essential for aluminum smelting), uranium processing, and as a flux in steelmaking. Fluorspar also is important in the manufacturing of welding rods. Through its use in the production of hydrofluoric acid, it is the main source of fluorine in almost all chemical applications. The United States produces fluorosilicic acid from phosphate processing; however, this potential domestic fluorine source has not been widely adopted for acid generation and metallurgical uses.
Gallium	Gallium is recovered primarily as a byproduct of processing bauxite; smaller quantities are recovered from zinc processing residues. No primary gallium has been recovered in the United States since 1987. Current production of low-grade, unrefined gallium is dominated by China; however, the United States can and does refine gallium to high-grade from primary low-grade gallium imports and from new scrap (recycled materials). Gallium finds major application in integrated circuits and optoelectronic devices such as light emitting diodes, photodetectors, and solar cells.
Germanium	Germanium is a minor constituent of some lead and zinc ores mined in the United States. The United States lacks processing facilities for recovering germanium from primary ores. Zinc concentrates containing germanium are exported to Canada and Belgium for processing and germanium recovery. The Unites States is reliant on imports of processed material or end products. Currently (February 2018), China is by far the world's largest germanium producer. Germanium is used in fiber optics, infrared optics, electronics, and solar cells.
Graphite (natural)	China is by far the largest producer of natural graphite, accounting for roughly two-thirds of world production. Only 4 percent of the world's natural graphite comes from North America, with no U.S. production in decades. Although natural graphite was not produced in the United States in 2016, about 98 U.S. firms, primarily in the Northeastern and Great Lakes regions, consumed graphite in various forms from imported sources for use in brake linings, foundry operations, lubricants, refractory applications, and steelmaking. Graphite's use in rechargeable batteries, as well as technologies under development (such as large-scale fuel-cell applications), could consume as much graphite as all other uses combined.
Helium	Helium is extracted from natural gas produced in the United States. Crude helium production exceeds domestic consumption, making the United States a net exporter of helium. Helium is used in magnetic resonance imaging, welding, semiconductor manufacturing, analytical and laboratory applications, engineering and scientific applications, and various other uses. The Bureau of Land Management manages the Federal Helium Program. Public law requires the Bureau of Land Management to dispose of all Federal helium-related assets when the remaining helium stockpile falls below 83 million cubic meters or no later than 2021.
Indium	Indium is primarily consumed as indium tin oxide, largely in flat-panel displays. Other notable uses of indium include semiconductors and low-temperature alloys. Indium is recovered as a byproduct of zinc ores. Although the United States has substantial production of zinc ore, there is no recovery of indium from ores in the United States. The United States is, therefore, exclusively reliant on imports. China is the world's largest producer of indium; however, Canada is the largest source of United States imports. New indium tin oxide (manufacturer's) scrap is recycled domestically, though there is limited information on the quantity of this production. There are no known commercial substitutes for indium tin oxide in flat-panel displays.

Table 2.1. Critical mineral commodity summaries.—Continued

[Commodities are listed alphabetically. Supply chain considerations were utilized in the selection process, meaning a commodity is included if any step in its supply chain is deemed problematic. Information in this table is from U.S. Geological Survey (2017, 2018, variously dated)]

Mineral commodity	Summary
Lithium	Lithium can be recovered from hard-rock deposits and brines. Lithium demand is expected to grow substantially because of its use in rechargeable batteries, particularly for electric vehicles. Lithium hydroxide also is used for cooling water chemistry control in pressurized water reactors and may be required in some advanced concept nuclear reactors (molten salt). The U.S. import reliance is moderate, but increasing foreign consumption in addition to U.S. demand growth has driven a substantial exploration boom.
Magnesium	Magnesium metal is produced from brines, which are virtually unlimited in comparison to demand. The United States only has one magnesium metal producer, which creates a potential single point of failure. Magnesium metal production is an important component of domestic titanium production; therefore, the loss of this domestic producer could result in broader effects. The United States only has a moderate import reliance on magnesium metal; Israel and Canada provide more than 50 percent of imports. There is substantial secondary recovery from magnesium castings and aluminum alloys that is comparable to the reported primary consumption.
Manganese	The United States has not mined manganese in decades and is reliant entirely on imports of manganese for ferroalloys, silicomanganese, and chemical compounds, and ore and alloy imports largely come from African nations and Australia. The United States does not possess economically viable resources, and manganese only is recycled incidentally during steel scrap processing.
Niobium	Most of the world's niobium production comes from one country, Brazil. Niobium is used primarily in high-strength low-alloyed steels that are necessary for infrastructure development and superalloys in the aerospace industry. Like the United States, China has no domestic niobium primary production and has invested in overseas acquisitions to secure its supplies. As developing countries construct their infrastructure and developed nations, including the United States, redevelop theirs, demand for niobium will likely increase.
Platinum-group metals	Platinum-group-metal (PGM) production is concentrated in South Africa and, to a lesser degree, in Russia and Zimbabwe. Although some primary PGMs are produced in the United States, as well as secondary (recycled) production, these are insufficient to satisfy domestic demand. Economic conditions, labor issues, and electricity shortages in South Africa in recent years have highlighted the risk associated with high production concentration in a single country. PGMs are used in a wide variety of applications ranging from electronics to anticancer drugs and biomedical devices to glass manufacturing equipment but are especially widely used as catalysts. Use in catalytic converters for the reduction of harmful emissions from internal combustion engines is essential but are likely to decrease with increased use of electric vehicles. Given their high value, PGMs have relatively high recycling rates except in their use in electronic applications because of the lack of collection of postconsumer electronics. Substitution of PGMs is limited because PGMs often are the best substitutes for other PGMs.
Potash	Potash denotes a variety of mined and manufactured salts that contain the element potassium in water-soluble form. Potash is used extensively in agriculture; fertilizers account for more than 85 percent of use, and the chemical industry accounts for the remainder. The United States is 90 percent reliant on imports to meet domestic demand for potash, and 85 percent of potash imports originate in Canada. Potash is produced in New Mexico and Utah from underground mining of ores and processing of brines. Estimated domestic potash resources total about 7 billion tons, whereas domestic reserves are estimated to be about 520 million tons. No substitutes exist for potassium as an essential plant nutrient and as an essential nutritional requirement for animals and humans.
Rare earth elements	With the closure of the Mountain Pass Mine in California, rare earth elements (REEs) are not mined in the United States. Most REEs, especially heavy REEs, are mined and processed in China. REEs are used in a wide range of applications ranging from magnets to phosphors for which there are limited substitutes. Furthermore, little postconsumer recycling happens for most of the REEs. Efforts by the Critical Materials Institute to develop substitutes and enhance recycling technologies are ongoing.
Rhenium	Rhenium is used primarily as an alloying agent in high-temperature steels for jet engines. Rhenium is produced as a byproduct of molybdenum, which itself is often a byproduct of porphyry copper mining. Although rhenium is present in domestic molybdenum-copper resources, the United States has insufficient processing capacity to meet domestic demand for rhenium. The United States ships rhenium-bearing molybdenum concentrates to Chile for recovery and imports refined rhenium. Rhenium recycling plays an important role in its global supply, but demand for new commercial and military jet aircraft will likely make it impossible for recycling alone to be sufficient. Given its high value and small market, substitution of rhenium is evaluated continually, and some substitutes have achieved commercial success. Reduced rhenium and rhenium-free alloys are being evaluated currently (2018) by major aerospace companies.

Table 2.1. Critical mineral commodity summaries.—Continued

[Commodities are listed alphabetically. Supply chain considerations were utilized in the selection process, meaning a commodity is included if any step in its supply chain is deemed problematic. Information in this table is from U.S. Geological Survey (2017, 2018, variously dated)]

Mineral commodity	Summary
Scandium	Scandium-bearing minerals are neither mined nor recovered domestically from mine tailings. The principal source for scandium metal and scandium compounds is imports from China. The principal uses for scandium are in aluminum-scandium alloys and solid oxide fuel cells. Other uses for scandium included ceramics, electronics, lasers, lighting, and radioactive isotopes used as tracing agents in oil refining.
Strontium	The United States is completely import reliant for strontium, sourcing all celestite from Mexico and other strontium compounds from Mexico, Germany, and China. Historically, the United States did have some domestic production of strontium carbonate, but this ended in 2006. Several companies do produce downstream chemicals domestically but in small amounts.
Tantalum	There has been no substantial U.S. domestic production of tantalum since the 1959. Moreover, tantalum is the only conflict mineral (the other three being tungsten, tin, and gold) whose primary production is mostly in the Great Lakes region of Africa, namely in Rwanda, the Democratic Republic of the Congo (Kinshasa), and, to a lesser extent, Burundi. Large, conventional tantalum mines in developed countries, including Australia and Canada, have largely been placed on care and maintenance indefinitely because of competition from lower-cost artisanal operations in Africa. Tantalum has a number of important uses in electronics, mainly in capacitors, and in superalloys that are used in jet engines and gas turbines.
Tellurium	Tellurium is recovered mainly as byproduct of anode slimes from certain copper refineries. Most of the tellurium contained in the copper anode slimes is not recovered currently (2018). Therefore, tellurium production in the United States and globally could be increased substantially without increasing copper production, but only under the appropriate economic conditions. Tellurium demand may increase substantially if the solar photovoltaic technology that uses tellurium, namely cadmium telluride, gains market-share. There are, however, a number of competing solar photovoltaic technologies. Aside from solar cells, tellurium's other major uses include thermoelectric devices and thermal imaging devices. Tellurium also is used in metallurgical applications.
Tin	Tin has a wide variety of end uses, including containers, chemicals, nonferrous alloys, and solders. U.S. mineral reserves of tin are small, and neither domestic mining nor smelting has happened in more than 20 years. However, tin has robust recycling from old (postconsumer) and new (manufacturing) scrap in the United States. The United States relies entirely on foreign imports of primary smelted tin; however, these imports are distributed broadly between South America and Southeast Asia. China is the world's largest miner of tin, providing more than one-third of the world's production.
Titanium	The United States is highly import reliant on titanium mineral concentrates, which have a variety of uses including pigments but also are required for metal production. The United States has a moderate import reliance on titanium metal (sponge), and imports mostly scrap and raw metal, while exporting finished wrought products. Titanium mineral reserves exist in the southeastern United States; however, these reserves are small compared to foreign supplies. Titanium recycling makes up a substantial part of domestic consumption, and few acceptable substitutes exist. Titanium is critical in aerospace components, in rotating parts in turbine engines, and for its use in corrosive environments.
Tungsten	Tungsten is produced domestically from imported materials or recovered from waste and scrap. China possesses the world's largest tungsten reserves and also is the largest producer with more than 80 percent of the world's primary production. China also supplies nearly 40 percent of tungsten material imported to the United States. Tungsten materials are widely recycled, which decreases foreign reliance. Substitutes for tungsten in high-wear and high-density applications exist and could reduce tungsten consumption, albeit at both increased price and performance loss.
Uranium	Uranium is critical for U.S. defense needs, energy production, the development of medical isotopes and energy generation in space vehicles and satellites. Current (2018) U.S. Department of Energy inventory is meeting most defense needs in the short term. However, U.S. sourced uranium will be needed in the future to meet defense requirements that, according to international agreements, must be free from peaceful use restrictions. Uranium also is critical in ensuring a reliable supply of fuel for the 99 nuclear power reactors that supply about 20 percent of U.S. electricity. Only 8 percent of uranium loaded into U.S. nuclear power reactors in 2016 was of U.S. origin; the remaining 92 percent was imported uranium. Under the American Isotope American Medical Isotope Production Act of 2012, the U.S. Department of Energy carries out a program of assistance for the development of fuels, targets, and processes for domestic molybdenum-99 medical isotope production. Uranium also is needed for production of fuel for certain space missions.

Table 2.1. Critical mineral commodity summaries.—Continued

[Commodities are listed alphabetically. Supply chain considerations were utilized in the selection process, meaning a commodity is included if any step in its supply chain is deemed problematic. Information in this table is from U.S. Geological Survey (2017, 2018, variously dated)]

Mineral commodity	Summary
Vanadium	Vanadium production is concentrated largely in a small number of foreign producers, including China (with more than one-half of world production), South Africa, Russia, and, increasingly, Brazil. The U.S. import reliance of vanadium is high, largely for consumption in alloy steel production. However, substantial domestic resources exist, although there is currently no primary production.
Zirconium and hafnium	Zirconium is recovered as a coproduct of mining and processing titanium and zircon mineral concentrates in Florida and Georgia. In addition to domestic sources of zirconium, the United States imports zircon mineral concentrates, mainly from South Africa, zirconium metal from China, as well as zirconium chemicals. Zirconium metal and hafnium metal are produced in Oregon and Utah from zirconium chemical intermediates. Typically, zirconium and hafnium are contained in zircon at a ratio of about 50 to 1, respectively. The leading consumers of zirconium metal are the nuclear energy and chemical process industries, whereas hafnium metal is used in superalloys for jet engines and land-based turbines.

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