Global Resilience Institute
at Northeastern University

Undergraduate Research:

How Long Can Rare Earth Elements Stay "Rare" for U.S. Supply Chains?

By Samuel Udell,
Co op Research Assistant

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Front Cover:

Image of Mountain Pass, the only operating Rare Earth Element mine in the United States owned by MP Materials

Photo Credits: Penny Meyer

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Preface

The supply chain disruptions associated with the COVID-19 pandemic has been a jolt to a general public who has long taken for granted that their consumer demands will always be matched with a ready supply. Whether it was a trip to the mall or a click on a website, they expected that goods could be readily found on store shelves or nimbly shipped to their doorsteps. What they had little appreciation of is the complexity of the global supply system that had made that possible.

Since the outbreak of the COVID-19 pandemic, there have accidents like the March 2021 grounding of the Ever Given in the Suez Canal, extreme weather events, and the Russian invasion of Ukraine that have continued to keep the global supply system off balance. Looking ahead, it is difficult to see how the system could ever get back to operating as it did in late 2019. This translates into the need for the U.S. government and companies to closely evaluate the sourcing of critical goods and materials and then evaluate their options for assuring they will have a reliable source of supply.

Many U.S. companies are looking closely at the need for onshoring, and nearshoring. In this paper, Samuel Udell makes the case that the federal government should be doing the same when it comes to Rare Earth Elements (REE), a group of 17 metallic elements that are critical to U.S. economic and national security interests. Many of these elements are needed in green technologies that will be key to achieving sustainability goals, but longstanding domestic concerns over the extraction process has translated into the U.S. relying heaving on supplies coming from China. There clearly are challenging environmental, economic, and security tradeoff issues that must be sorted through if we are to achieve optimal resilience outcomes.

Samuel has researched and written How Long Can Rare Earth Elements State "Rare" for U.S. Supply Chains?" while working as a Northeastern undergraduate member of the Global Resilience Institute's research team. This timely paper succinctly presents the facts and analysis to inform a discussion on this important issue.

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Professor and Founding Director

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Samuel is a senior at Northeastern University pursuing a Bachelor of Science in Economics and Business Administration with a concentration in Finance. Before joining the GRI research team as a Research Assistant, Sam was a Legal Analyst at State Street Corporation in Boston, Massachusetts. He looks forward to exploring his interests in government policy and research at the GRI this Spring.

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How Long Can Rare Earth Elements Stay "Rare" for U.S. Supply Chains?

Rare Earth Elements (REE) are a group of 17 metallic elements that are critical for modern technologies, renewable energy, and military applications. As the United States and the rest of the world shift away from fossil fuels and toward green technologies, demand for Rare Earth Elements is expected to grow tremendously. Rare Earth Elements are found sporadically around the globe, however, economic viability has limited extraction to a few major mines mostly located in China. Following U.S. Executive Order 14017, the United States is beginning to break away from reliance on China and strengthen domestic supply chain resiliency, especially for Rare Earths.

On February 22, 2022 the U.S. Geological Survey, a branch of the U.S. Department of Interior, released it's 2022 final list of critical minerals. Amongst this list of 50 elements deemed essential to U.S. economic and security interests are all 17 Rare Earths, a group of magnetic and luminescent elements that consist of the lanthanide series, Scandium, and Yttrium. These metals possess unique geochemical properties that make them necessary in the development of military equipment, renewable energy technologies, semiconductors, electric vehicle batteries, and high-tech consumer products.

Although dubbed "Rare Earth", deposits are common in the Earth's crust and are more abundant on average in the Earth's crust than silver, gold, or platinum. However, the high environmental impact and financial costs of extracting the isolated minerals are burdensome, limiting excavation to a few large mines located primarily in China. As the majority of these metals are sourced from outside of the United States, a disruption of supply poses a severe risk to U.S. national security, economic interests, and supply chain resiliency. Furthermore, with the Biden Administration's plans to push the United States towards net-zero carbon emissions by 2050, securing a stable supply of Rare Earth will also be essential to U.S. decarbonization efforts as Rare Earths are primary components of electric vehicle and hybrid batteries, high capacity generators, wind turbines, and solar panels. To address these concerns, the Biden-Harris Administration passed Executive Order 14017 on February 24th, 2021, establishing a 100-day strategic supply chain review for major critical mineral and material supply chains.

F-35 Fighter Jets for the U.S. Air Force each require 100s of kilograms of REEs

In June 2021, the White House posted a summary report of its findings from E.O. 14107 with contributions from the Department of Commerce, Department of Energy, Department of Defense, and the Department of Health and Human Resources. In unison with President Biden's "Build Back Better Framework", the report highlights 23 recommendations for the U.S. federal government to become more involved in supply chain resiliency for semiconductors and advanced packaging, large capacity batteries, critical minerals and materials, and pharmaceuticals through strategic investments, domestic and equitable job growth, and safety and environmental regulations. For critical minerals and materials, led by the Department of Defense, the White House found several risk factors for the Rare Earth supply chain. Amongst these include increased net import reliance; a high concentration of supply; several single-source suppliers; price shocks; skill and human capital gaps; and the presence of conflict minerals, organized crime, and forced labor.

According to the U.S. Geological Survey, "of the 35 minerals or mineral material groups identified as 'critical minerals' [in] 2018, the United States was 100% net import reliant on 14, and an additional 15 critical mineral commodities had a net import reliance greater than 50% of apparent consumption". In 2021, the United States was greater than 90% Net Import Reliant on Rare Earths (100% in 2020) and 100% Net Import Reliant on Yttrium and Scandium from China, Japan, Malaysia, Estonia, and the Republic of Korea (Exhibit 1). Net Import Reliance of over 90% implies that over 90% of materials consumed in the United States are supplied by foreign imports as domestic production cannot meet demand.

To make matters worse, the United States is sourcing many of these strategic materials from a very limited number of countries and producers. According to the Department of Defense, 37 shortfall strategic critical materials were subject to a Foreign Market Dominator. They also noted that out of 53 unclassified shortfall materials, "a domestic sole-source provider exists for 29...and 18 materials have no domestic production at all", while 15 supply chains, including Rare Earth Permanent Magnets, have a "concentration of supply... so extreme that U.S. or global production is concentrated in a single source" (The White House).

If a disruption were to occur, the United States would not have enough strategic materials for the civilian and defense sectors and would be subject to price shocks, geopolitical tensions, and severe strains on vital industries. According to the Congressional Research Service, Rare Earth Elements are used in the defense sector for guidance and control systems (such as Tomahawk cruise missiles and Predator unmanned aircrafts), defense electronic warfare (such as jamming devices, area denial systems, and electromagnetic railguns), targeting and weapon systems, electric motors, and joint strike fighters. For each F-35 fighter jet alone, 417kg of Rare-Earth materials is required. Yet, "even though the U.S. Armed Forces have vial requirements from strategic and critical materials, the essential civilian sector would likely bear the preponderance of harm from a disruption event," as the Department of Defense would have to siphon strategic material through the Defense Production Act for National Security. "This finding is consistent across every modeling excursion by the DoD since 2009" (The White House).

Thus, for the greater U.S., a minor disruption in critical minerals would seep deeply into the entire economy. As noted by the Department of Defense, "annual domestic mining activities valued at less than $100 billion, enable more than $3 trillion in domestic-value added industry sectors, out of a $20 trillion economy" (The White House). For Rare Earths, "approximately $613 million in U.S. consumption of Rare Earth elements unlocks $496 billion in economic activity in essential civilian sectors including petroleum refining, electromedical device manufacturing, automotive manufacturing, and search, detection, and aeronautical instrument manufacturing." For the renewable energies sector, up to 600 kg of Rare Earth Elements are required to operate just one wind turbine and about one kilogram is needed for every electric vehicle battery.

However, to revamp mining of U.S. critical minerals and Rare Earths could take decades. Further Department of Defense modeling estimates that "a reasonable industry benchmark for the development of mineral-based strategic and critical materials project is not less than ten years" (The White House). Moreover, there are several other integral challenges besides time. There has been a steady decline in U.S. ingenuity and morale for mineral extraction for several decades. Over the last 35 years, the number of colleges and universities with mining and extractive metallurgy production programs has steadily decreased [or eliminated altogether] ... A principal reason for this decline in education and knowledge is the reduced U.S. demand for mining engineers and technicians. With suppressed demand, the U.S. mining industry is suffering from labor shortages, low mining salaries, and less higher education programs.

By February 22, 2022 the Department of Defense acted promptly, awarding $35 million to MP Materials, the only currently-operating Rare Earth mine and separation facility in the United States, to build a U.S. Heavy Rare Earth Separation facility. This decision came one week after the Department of Energy released an RFI for a new domestic Rare Earth Element Separation Facility in Illinois. As of March 30, 2022 President Biden has gone as far as to consider invoking the Defense Production Act (DPA) of 1950 to increase the mining of critical minerals while the (FY) 2022 National Defense Authorization Act requested additional rare-earth oxides. These initiatives have represented a fundamental shift in U.S. policy towards Rare Earths and Critical Minerals, an issue which has increasingly seen bipartisan support. In September of 2020, President Donald Trump also passed a similar executive order, E.O. 13817, to identify critical minerals, support funding from the federal government, and decrease reliance on China. Thus since 2019, the United States has been pouring more funding into Rare Earth both domestically and abroad.

U.S. President Joe Biden is contemplating using the Defense Production Act of 1950 to boost mining of Critical Minerals

The Loss of U.S. Dominance

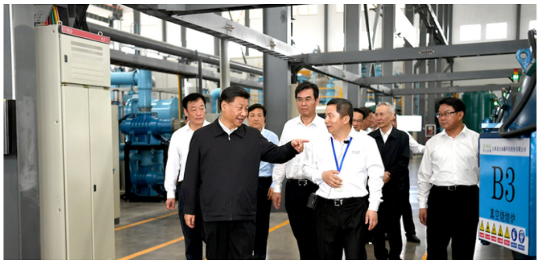
Historically, the United States lost its grip on the Rare Earth industry due to shifting national security policies following the end of the Cold War, environmental concerns, high economic costs, and the rise of the Chinese Communist Party. During World War II and the Manhattan Project, the U.S. became familiar with Rare Earths with the advent of the nuclear bomb. Requiring steady amounts of isolated uranium, U.S. scientists had to separate the uranium ore which frequently occurs with Rare Earth Elements. In fact, as early as 1939, the German Scientists Hahn and Strassman discovered the neutron-induced nuclear fission of uranium and identified rare earth elements in fission products. As demand for uranium grew, the United States funded the Mountain Pass Mine in California, which inadvertently led to a massive increase in the supply of Rare Earth Elements rather than uranium. As new applications for Rare Earths began to emerge, such as the usage of Europium in the first colored televisions, the United States emerged as a leader in the space.

From the 1960's to 1980's the United States maintained its grip on Rare Earths as the Cold War encouraged more uranium exploration and government funded research and development into new applications for Rare Earths, especially for the military. Over the next several decades, both the United States and Russia found several new military applications for Rare Earths. In the early 1960's, research by the U.S. Air Force at Patterson Air Force Base led to the development of the Samarium-cobalt magnet. In the 1980's, Russia used scandium oxide to improve the weight and durability of their MIG 29 fighter jets in 1985. During the same time, applications for Rare Earths in the corporate and industrial sectors began to emerge as well. In 1984, General Motors and Sumitomo Metals invented the neodymium magnet, found in hard drives, mobile phones, electric engine starts, and even windshield wipers. In 1986, the Nickel Metal Hybride Battery was patented by Stanford Ovshinsky, which is used heavily in consumer electronics and eventually the first hybrid cars, such as the Toyota Prius in 2001.

By the end of the Cold War, the United States no longer relied as heavily on Rare Earth elements for its National Defense Stockpile program as national security threats dwindled around the globe. With the fall of the Iron Curtain, governments around the world began to reduce trade restrictions and the era of globalization began to take shape, leading to the broad shift in U.S. manufacturing and mining abroad. Up until the early 2000's the U.S. allowed the Rare Earth industry to operate under normal market conditions, while other countries began to subsidize the sector. However, as global demand and prices fell, coupled with new U.S. environmental policies under the Clinton Administration, the U.S. closed its only Rare Earth mine, MP Materials, in 2002.

China Doubles Down

Due to the economic phenomenon known as the "Race to the Bottom", the Rare Earth industry flourished in China. Aligning with the geopolitical ambitions of the Chinese Communist Party (CCP), China embraced Rare Earth mining with a high supply of cheap labor, favorable domestic policies, laxed environmental and human



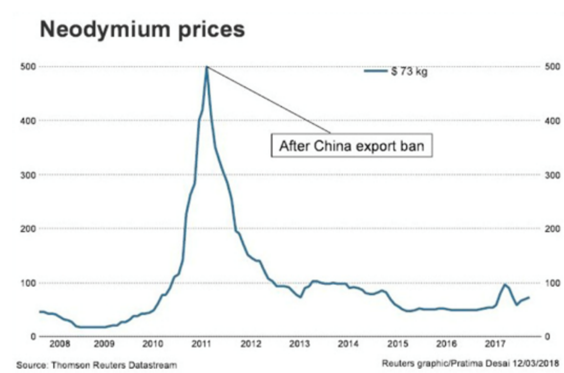
Xi Jinping, General Secretary of the Chinese Communist Party, visits a Rare-Earth Production Facility in Ganzhou, China (Xinhua/Xie Huanchi via Getty)

health protocols, and a disregard for free market principles. Through China's socialist market economy, China has been able to prop up it's Rare Earth mining industry through excessive government support and strategic purchases of foreign intellectual property. In 1995, the CCP bought a subsidiary of GM's Magnequench that was a leader in manufacturing permanent magnets. In 2009, the CCP attempted to purchase a majority stake of Lynas Corporation, the largest Rare Earth mine outside of China.

Today, China is a "foreign market dominator" and has an estimated 55% control on rare earths mining capacity and 85% control on rare earths refining in 2020. This grip on the Rare Earth market has granted China disproportionate control and acts as a powerful weapon for national security.

Similar to the United States, China began to get involved with Rare Earths during the development of their nuclear weapons program. "Following China's first nuclear weapons test in 1964, central government leaders ordered a reorganization of the country's research and development programs for rare earth and other non-ferrous metals. Xu Guangxian's work on isolating uranium was crucial to his discovery of the Cascade Theory of Countercurrent Extraction, which revolutionized Rare Earth production and greatly increased the global rare earth supply in the 1970s. Xu's discovery marked the beginning of China's technological superiority in the rare earth sector, which was recognized in the early 21st century" (Fifarek et al.).

Over the last several months, prices of Rare Earth Elements have risen to levels not seen since their last major run in 2011, where after a territorial dispute between Japan and China in the Senkaku Islands, China heightened export quotas on Rare Earths, artificially raising prices and prompting an international World Trade Organization dispute. At the time, this event opened the world to the importance of Rare Earth elements and "set off a wave of R&D, substation, and some supply-side investments, but by the time Rare Earth prices return to 'normal' after 2014, the market pressures to diversify supply chains waned" (The White House). By the peak of market demand there were approximately 275 rare earth projects under development by 180 publicly-traded companies in 30 countries, excluding projects in China, Russia, and India. (Advanced Rare-Earth Project, TechmetalsResearch.com). Yet, by April of 2021, only two of these projects entered full-scale operation and two others remain in pilot-plant production–a combined success rate of 1.5% over the past decade".



Recently, with diminished U.S.-Sino relations and calls for "Made in America", and the global shift towards renewable energies, demand for Rare Earths and calls for diversification have resurfaced. As global economies demand more Rare Earth, global supply chains will continue to be at risk of disruption from Chinese intervention, other geopolitical and economic tensions, or natural disasters and supply shocks. As recently as 2019, amidst growing Sino-US economic tensions, the Chinese Communist Party threatened to restrict

"The Middle East has oil, China has rare earths." – Deng Xiaoping, Ex-Paramount Leader of the People's Republic of China

Rare Earth exports to directly impact the U.S. Defense industry. In February of 2022, following the Russian invasion of Ukraine, the world has been denied access to Russia's 25% of global rare earth deposits. Consequently, in March of 2022, China attempted to further strengthen its waning grip on the Rare Earth market by consolidating it's 3 largest Rare Earth companies into China Rare Earth and by cutting domestic capacity by 25% due to the current border closure with Myanmar.

The U.S. Resurgence

Across the United States, the private sector has responded promptly to the growing calls for new domestic supply chains for critical minerals outside of China. Expecting generous support from the Biden Administration, Rare Earth mines have begun to sprout and source funding for new exploration while universities and technology companies have begun to look into more safe and effective extraction methods. In 2021, a U.S. company made a shipment of 20 tons of rare earth carbonate to a rare earths supplier in Estonia, effectively the first step in a new United States-to-Europe Rare Earth supply chain. Outside of the United States, Canada, Australia, Japan, and Europe all possess the capabilities to extract Rare Earths and have increased investment in the sector.

As the United States revamps it's supply chains for the technologies of the futures, the Department of Defense has outlined several potential improvements to the Rare Earth Supply Chain including a new sustainability standard in the Rare Earth sector and the inclusion of a "sustainability requirement" for future U.S. government purchasing. It also requested the expansion of sustainable domestic production and processing capacity, with a heavy focus on recycling and secondary resource extraction to reduce environmental impact. Lastly, the Department of Defense expanded upon increased investment in the space through the Defense Productions Act, increased efforts to reclaim mining waste, and to grow the U.S. stockpile through the DPA and other programs, the promotion of interagency research and development to support sustainable production and a technically-skilled workforce, and to encourage work with allies and partners to strengthen global supply chain transparency.

Neodymium Ore, an input for magnets found in Electric Vehicle batteries

Conclusion:

As the United States and the globe advance into the 21st century, the ability to produce technology reliably will become increasingly important. With nearly 1 kg of Rare Earths in each battery of an electric vehicle, "Rare Earths" may need a name change.

Sources & Further Readings:

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Images:

a. Mountain Pass Mine on Title Page: nsenergybusiness

b.F16 Fighter Jets: istockphoto

c. Joe Biden: eenews

d. Xi-Jinping in factory: businessinsider

e. Neodymium price chart with ban label: interaksyon.philstar

f. Neodymium Ore: asiatimes

g. Exhibit 1, 5, 6, 7: whitehouse

h. Exhibit 2: cnbc

i. Exhibit 3: geology

j. Exhibit 4: chinapower.csis

Appendices & Exhibits:

Exhibit 1: 2021 U.S. Net Import Reliance

Figure 2.—2021 U.S. Net Import Reliance[1]

Commodity	Net import reliance as a percentage of apparent consumption	Major import sources (2017–20)[2]
ARSENIC, all forms	100	China, Morocco, Belgium
ASBESTOS	100	Brazil, Russia
CESIUM	100	Germany, China
FLUORSPAR	100	Mexico, Vietnam, South Africa, Canada
GALLIUM	100	China, United Kingdom, Germany, Ukraine
GRAPHITE (NATURAL)	100	China, Mexico, Canada, India
INDIUM	100	China, Canada, Republic of Korea, France
MANGANESE	100	Gabon, South Africa, Australia, Georgia
MICA (NATURAL), sheet	100	China, Brazil, Belgium, India
NEPHELINE SYENITE	100	Canada
NIOBIUM (COLUMBIUM)	100	Brazil, Canada
RUBIDIUM	100	Germany
SCANDIUM	100	Europe, China, Japan, Russia
STRONTIUM	100	Mexico, Germany, China
TANTALUM	100	China, Germany, Australia, Indonesia
VANADIUM	100	Canada, China, Brazil, South Africa
YTTRIUM	100	China, Republic of Korea, Japan
GEMSTONES	99	India, Israel, Belgium, South Africa
TELLURIUM	>95	Canada, Germany, China, Philippines
POTASH	93	Canada, Russia, Belarus
IRON OXIDE PIGMENTS, natural and synthetic	91	China, Germany, Brazil
RARE EARTHS,[3] compounds and metals	>90	China, Estonia, Malaysia, Japan
TITANIUM, sponge	>90	Japan, Kazakhstan, Ukraine
BISMUTH	90	China, Republic of Korea, Mexico, Belgium
TITANIUM MINERAL CONCENTRATES	90	South Africa, Australia, Madagascar, Mozambique
ANTIMONY, metal and oxide	84	China, Belgium, India
STONE (DIMENSION)	84	China, Brazil, Italy, India
CHROMIUM	80	South Africa, Kazakhstan, Russia, Mexico
PEAT	80	Canada
SILVER	79	Mexico, Canada, Chile, Poland
TIN, refined	78	Indonesia, Peru, Malaysia, Bolivia
COBALT	76	Norway, Canada, Japan, Finland
DIAMOND (INDUSTRIAL), stones	76	South Africa, India, Congo (Kinshasa), Botswana
ZINC, refined	76	Canada, Mexico, Peru, Spain
ABRASIVES, crude fused aluminum oxide	>75	China, France, Bahrain, Russia
BARITE	>75	China, India, Morocco, Mexico
BAUXITE	>75	Jamaica, Brazil, Guyana, Australia
SELENIUM	>75	Philippines, China, Mexico, Germany
RHENIUM	72	Chile, Canada, Kazakhstan, Japan
PLATINUM	70	South Africa, Germany, Switzerland, Italy
ALUMINA	58	Brazil, Australia, Jamaica, Canada
GARNET (INDUSTRIAL)	56	South Africa, China, India, Australia
MAGNESIUM COMPOUNDS	55	China, Brazil, Israel, Canada
ABRASIVES, crude silicon carbide	>50	China, Netherlands, South Africa
GERMANIUM	>50	China, Belgium, Germany, Russia
IODINE	>50	Chile, Japan
TUNGSTEN	>50	China, Bolivia, Germany, Canada
CADMIUM	<50	Australia, China, Germany, Peru
MAGNESIUM METAL	<50	Canada, Israel, Mexico
NICKEL	48	Canada, Norway, Finland, Australia
COPPER, refined	45	Chile, Canada, Mexico
ALUMINUM	44	Canada, United Arab Emirates, Russia, China
DIAMOND (INDUSTRIAL), bort, grit, dust, and powder	41	China, Ireland, Republic of Korea, Russia
LEAD, refined	38	Canada, Mexico, Republic of Korea, India
PALLADIUM	37	Russia, South Africa, Germany
FELDSPAR	32	Turkey
SILICON, metal and ferrosilicon	32	Russia, Brazil, Canada, Norway
SALT	29	Chile, Canada, Mexico, Egypt
MICA (NATURAL), scrap and flake	28	Canada, China, India
LITHIUM	>25	Argentina, Chile, China, Russia
BROMINE	<25	Israel, Jordan, China
ZIRCONIUM, ores and concentrates	<25	South Africa, Senegal, Australia, Russia
PERLITE	23	Greece, China, Mexico, Turkey
VERMICULITE	20	South Africa, Brazil

[1]Not all mineral commodities covered in this publication are listed here. Those not shown include mineral commodities for which the United States is a net exporter (boron; clays; diatomite; gold; helium; iron and steel scrap; iron ore; kyanite; molybdenum; rare earths, mineral concentrates; sand and gravel, industrial; soda ash; titanium dioxide pigment; wollastonite; zeolites; and zinc concentrates) or less than 20% net import reliant (abrasives, metallic; beryllium; cement; gypsum; iron and steel; iron and steel slag; lime; nitrogen (fixed)—ammonia; phosphate rock; pumice; sand and gravel, construction; stone, crushed; sulfur; and talc and pyrophyllite). For some mineral commodities (hafnium; mercury; quartz crystal, industrial; thallium; and thorium), not enough information is available to calculate the exact percentage of import reliance.

[2]Listed in descending order of import share.

[3]Data include lanthanides.

Exhibit 2: Locations and Size of Rare Earth Metal Mines

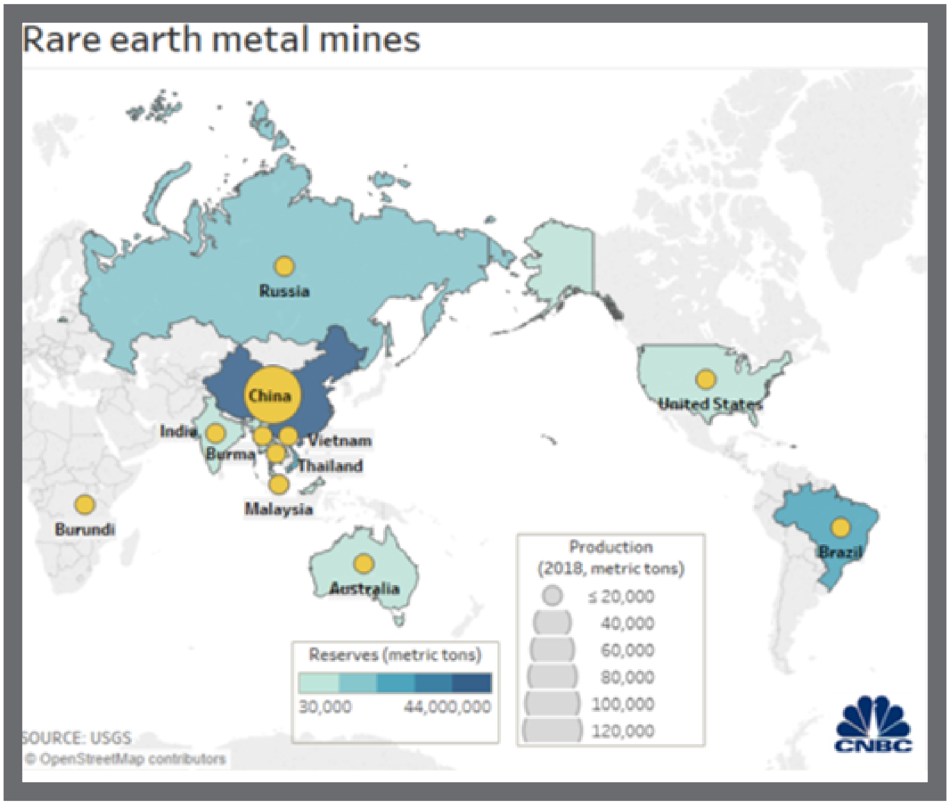

Exhibit 3: Global Production of Rare Earth Elements

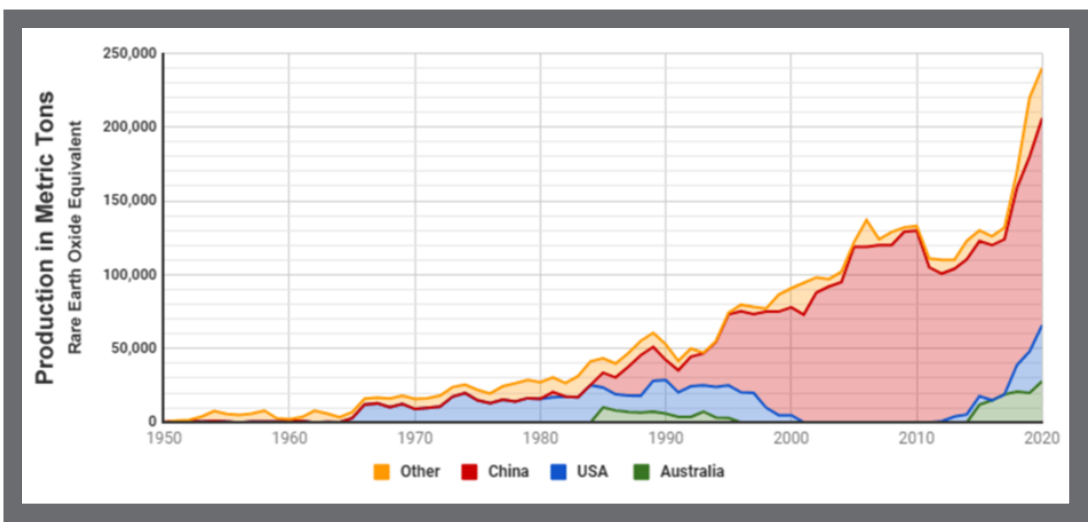

Exhibit 4: Breakdown of Global Rare Earth Exports (2008-2018)

Breakdown of Global Rare Earth Exports (2008-2018)

Country	Export Volume (metric tons)	Share (%)
China	407,886.6	42.3
USA	89,467.1	9.3
Malaysia	87,696.1	9.1
Austria	87,055.1	9.0
Japan	68,412.9	7.1
Rest of World	223,172.7	23.2

Exhibit 5: China's Share of Global Primary Production (1990-2018)

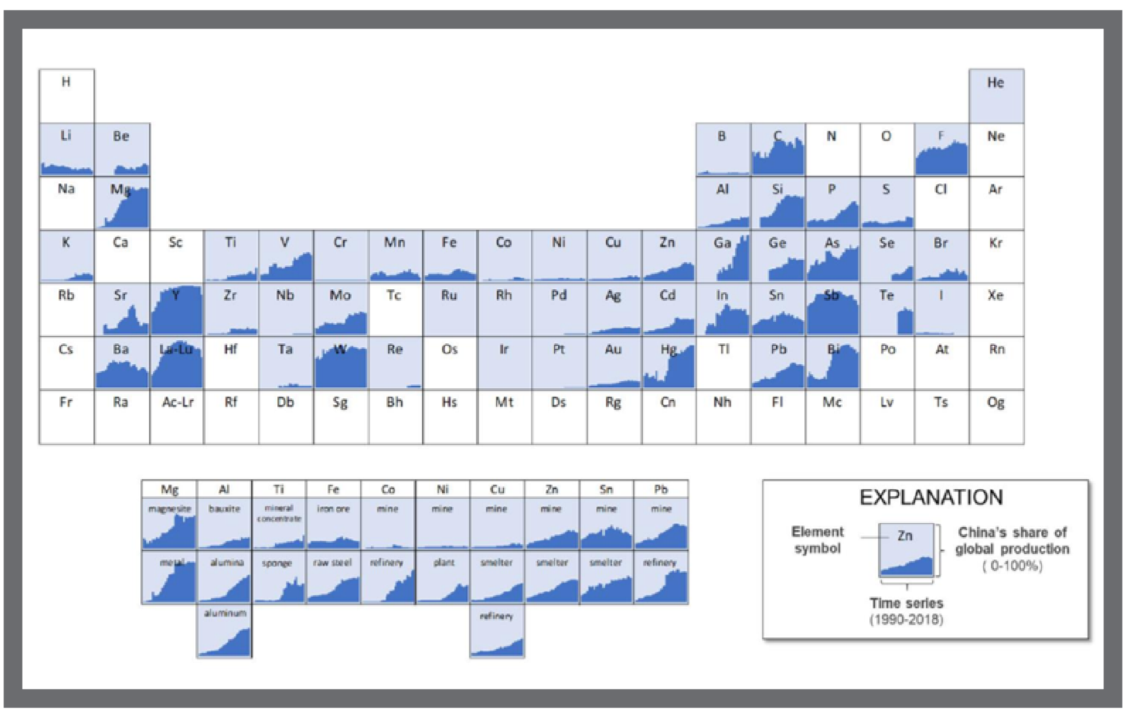

Exhibit 6: Domestic Producers for Unclassified Shortfall Materials

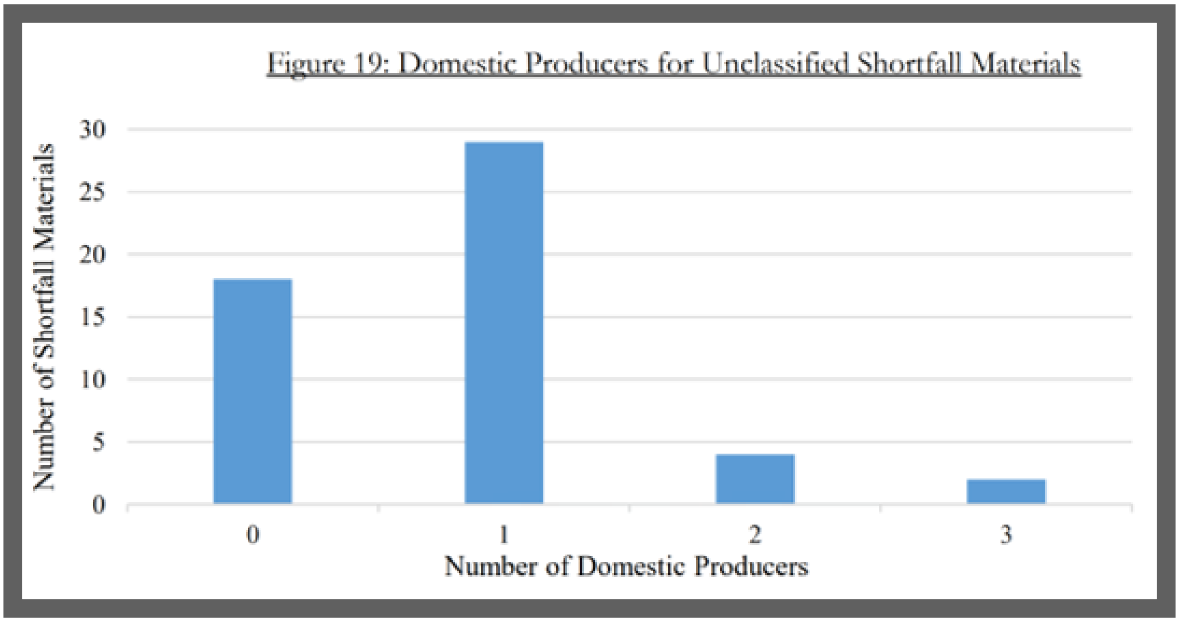

Exhibit 7: Major Applications of Rare Earth Elements

Element		Major Applications
LREE	**Lanthanum**	Fluid catalytic cracking for petroleum refining, nickel metal hydride (NiMH) batteries, metallurgical applications, glass and polishing ceramics lighting.
	Cerium	Automobile catalysts and additive, FCC additives, catalysts, metallurgy, polishing, powders and glass and others such as fertilizer, paint drying, and a stabilizer in plastics. Applications often overlap with lanthanum.
	Praseodymium	NdFeB, metallurgical applications, pigments, batteries, and catalysts.
	Neodymium	NdFeB magnets, glass and ceramics applications such as ceramic capacitors, metallurgical applications such as a minor alloying element for iron and steel alloys and magnesium alloys, luminophores, and other applications such as NiMH batteries, catalysts, and lasers. NdFeB magnets are used in products such as computer hard disk drives, magnetic resonance imaging (MRI), precision guided munitions, automotive motors, wind turbines, and loudspeakers.
	Samarium	Samarium cobalt permanent magnets, which are used in electronics (including military systems), automobiles, aerospace, pumps, and medical devices. Other applications include infrared absorption glass, optical glass, fuel cells, for nuclear applications, and capacitors for microwave frequencies.
HREE	**Europium**	Phosphors and luminophores, which are used in TV and computer screens, compact fluorescent lighting, light emitting diodes (LEDs), and sensors. Other applications include nuclear and medical applications and for some specialty alloys and lasers.
	Gadolinium	Metallurgical applications such as magnetic refrigeration, magnesium alloys, and specialty alloys. Also used in small amounts for samarium cobalt magnets. Other uses include MRI contrasting agent and phosphors for dental and medical applications.
	Terbium	Phosphors (green) for displays, LEDs, and in medical applications, in permanent magnets, and for other applications such as high-temperature fuel cells, lasers, and magnetostrictive alloys for solid-state transducers and actuators used in sonar and other dual use technologies.
	Dysprosium	Neodymium iron boron permanent magnets in which it makes up generally about 0.8 percent to 1.2 percent by weight of the magnet; magnetostrictive alloys.
	Holmium	Magnets, magnetostrictive alloys for sensors and actuators.
	Erbium	Nearly all erbium is used in polishing and in highly specialized glass lens applications and fiber optics.
	Thulium	Portable X-ray devices, research, and a dopant in solid-state lasers and highly specialized fiber optics.
	Ytterbium	Metallurgical applications for rare earth magnesium alloys and specialty aluminum alloys.
	Lutetium	Used in medical equipment and small quantities in phosphors.
	Yttrium	Yttrium-stabilized zirconia (YSZ) ceramics, phosphors, and metallurgy. Some specific applications include thermal barrier coatings, lasers, oxygen sensors, and solid electrolytes for solid oxide fuel cells (SOFCs). Phosphors, optical glasses, rotary-wing aircraft alloys, and nickel-metal hydride (NiMH) batteries.
	Scandium	Solid oxide fuel cells (SOFC), aluminum alloys for aerospace and sporting goods, scandium-sodium lamps for outdoor venues, laser, optoelectronic materials, LEDs.

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