Critical Minerals in Nuclear Supply Chains

P Porter Bradley[1], MR Deinert[1,2]

[1]Nuclear Science and Engineering, [2]Payne Institute for Public Policy

The Colorado School of Mines

Nuclear energy accounted for near half of emissions-free electricity generation in the US in 2022 with the industry encompassing ~ 500,000 jobs[1]. The nuclear supply chain spans a broad spectrum of activities, ranging from uranium extraction and enrichment to the construction, operation, decommissioning, and waste management of nuclear plants. In the coming years, the nuclear sector is set to diversify further as advanced nuclear facilities, with various coolants, fuels, sizes, and delivery methods, are developed and deployed to provide low-carbon energy for electricity and industrial applications[1]. The U.S. nuclear industry is actively engaged in international trade, subject to strict government regulations and oversight, which includes both imports, particularly for uranium and certain other materials with limited domestic production, and exports. China, Russia, and other global competitors are increasingly involved in numerous nuclear projects worldwide, further intensifying the demand for materials essential for the construction and operation of nuclear reactors[1]. Many of these materials are also required for renewable and energy systems which increases competition and cost[2].

In February of 2021, the Office of the President of the United States released Executive Order 14017[3]. It ordered a comprehensive review of supply chains with 100-day and 1-year review deadlines for numerous agencies and government departments to submit relevant reports on supply chains that affect the economic prosperity and national security of the United States. In February of 2022, the U.S. Department of Energy (DoE) released a response entitled “America’s Strategy to Secure the Supply Chain for a Robust Clean Energy Transition.” This was supplemented by thirteen “Deep Dive Assessments of the Supply Chain” for various parts of the energy sector[4]. One of these focused on nuclear energy[1]. In 2022, the US DoE also released its roadmap for advanced materials manufacturing[5] in the nuclear sector also underscoring a growing concern about the impact that materials, and their processing, could have on a sustainable nuclear power sector.

The existing nuclear supply chain is primarily designed to support the operation of large grid-scale nuclear reactors which in the United States are Light Water Reactors (LWRs). The

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[1] Nuclear Energy, Supply Chain Deep Dive Assessment, U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

[2] The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions, IEA, 2021

[3] “America’s Supply Chains,” Federal Register, March 1, 2021, https://www.federalregister.gov/documents/2021/03/01/2021-04280/americas-supply-chains.

[4] “Securing America’s Clean Energy Supply Chain,” Energy.gov, n.d., https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain.

[5] Advanced Materials and Manufacturing Technologies 2022 Roadmap, ANL-23/12

infrastructure necessary for their operation and maintenance is extensive, encompassing various components such as vessels, piping, castings, structural steel, concrete, cabling, and instrumentation and controls. In the United States, the construction of new large LWRs is currently restricted to just two AP1000 plants located in Georgia. Notably, the AP1000 supply chain is global, with contributions coming from countries such as South Korea, Japan, Italy, Switzerland, Brazil, Canada, and the United States. The next generation of "advanced" reactors is expected to feature Small Modular Reactors (SMRs) and Microreactors with high-temperature gas, liquid metal, and molten salt variants that will increase the use of some critical materials. Because of the long timeline for certification of new materials for use in commercial reactors, typically two decades or more, the same materials used in LWR's are expected to be used for construction of advanced reactors[6]. It should be noted that fuels, including uranium, are no longer categorized as critical minerals since Energy Act of 2020 within H.R. 133 - Consolidated Appropriations Act[7], defined critical fuels and prohibits them from also being defined as critical minerals.

Both conventional and advanced reactors cannot be built without numerous critical materials. The design and size of LWRs require large quantities of steel and concrete. Because of its importance in construction in general, cement is widely produced domestically, with at least 96 plants in 34 states plus 2 in Puerto Rico currently in use**Error! Bookmark not defined.**. However, high density concrete for nuclear applications often also contains additional steel or barite for radiation shielding purposes[8]. While steel is produced domestically, nuclear-grade steels require minerals for which there is a high import reliance. These include chromium and nickel, ranked 1st and 3rd in the kg needed/MW power metric among non-emitting generation technologies[9]. The United States has an 83% net import reliance on chromium and a 56% net import reliance on nickel**Error! Bookmark not defined.**. The major chromium producers are South Africa and Kazakhstan, while the major nickel producers are Canada, Norway, and Australia, in that order**Error! Bookmark not defined.**. Copper, for its role in electrical systems, is ranked 2nd in terms of kg/MW for nuclear energy production among the non-emitting generation technologies[1]. However, with ample domestic supply, it is not noted as a mineral for concern**Error! Bookmark not defined.**. The same is true for molybdenum and manganese**Error! Bookmark not defined.**, which are ranked 4th and 5th in terms of kg/MW for nuclear among non-emitting generation technologies[1].

Other minerals noted for their use in the nuclear industry include holmium for its use as a burnable poison and niobium for its thermal-neutron transparency and use in in coatings and alloys

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[6] Aguiar, J.A., Jokisaari, A.M., Kerr, M. *et al.* Bringing nuclear materials discovery and qualification into the 21st century. *Nat Commun* **11**, 2556 (2020). https://doi-org.proxy.library.cornell.edu/10.1038/s41467-020-16406-2

[7] Congress.gov. "Text - H.R.133 - 116th Congress (2019-2020): Consolidated Appropriations Act, 2021." December 27, 2020. https://www.congress.gov/bill/116th-congress/house-bill/133/text.

[8] Daungwilailuk et al, Use of barite concrete for radiation shielding against gamma-rays and neutrons, Construction and Building Materials, 326, 4 April 2022, 126838

[9] "The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA," IEA, n.d., https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

used in nuclear components **Error! Bookmark not defined.**. Niobium has a 100% net import reliance, with 88% of global production coming from Brazil**Error! Bookmark not defined.**. Tungsten, which has a 50% import reliance, can be substituted for lead or depleted uranium in radiation shielding and high-density and military applications**Error! Bookmark not defined.**. The vice versa is also true. Barite, which is used as radiation shielding in nuclear power plants, has a 75% net import reliance. Major sources of the mineral include China, India, Morocco, and Mexico. It is mined domestically in Nevada and Alabama, but the data is listed as proprietary**Error! Bookmark not defined.**.

Besides the initial construction materials, numerous other critical minerals are needed for continued maintenance, replacement, and other operation actions. Lithium is used in small quantities, about 300 kg/year for the entire PWR fleet, to maintain pH chemistry within the water used in the core[1]. While there is domestic lithium production, it requires enrichment to greater than 99% Li^7 to be usable in reactors, for which there is a currently no domestic US capacity. Instead, and before the war in Ukraine, most of the Li^7 enrichment capacity came from Russia[10]. For natural lithium production, the top three producers are Australia, which produces more than half of the world's supply, followed by Chile, and China**Error! Bookmark not defined.**. A variety of processed minerals may be used as neutron absorbing materials in reactor control rods. These include silver-indium-cadmium alloys typically used for control rods in Pressured Water Reactors (PWRs). The United States has a 100% net import reliance of indium, with 40% of global production from China and 31% from South Korea, followed by Canada and France**Error! Bookmark not defined.**. Silver and cadmium are often described as critical minerals, but of less concern as there are domestic suppliers[1]. These types of control rods can be replaced with hafnium-based rods. Hafnium is produced as a by-product of zirconium production. This ties the costs and reserves of these minerals to each other. Both are used in the nuclear energy industry, though zirconium is a common alloying material for cladding, and for advanced metal fuels. The US has less than a 50% import reliance on zirconium ores and concentrates, with major international producers being South Africa, Senegal, Australia, and Russia**Error! Bookmark not defined.**. One company extracts zirconium in both Florida and Georgia, with another company processing the mineral from sand tailings in Florida. Hafnium and zirconium are produced from chemical intermediaries in Oregon and Utah. There is a limited potential for substitution for zirconium and hafnium with certain stainless-steel alloys (such as SS 304) and tantalum when control rods with high temperature and corrosion resistance are needed. Europium, sometimes used in nuclear control rods, can be used in building and operating nuclear reactors in its high-purity Europium Oxide form**Error! Bookmark not defined.**. Samarium can also be used as an absorber in nuclear reactors but is very rare.

While many advanced reactors, including light-water based SMRs, are likely to use the same or similar materials and supply chains as conventional LWRs, other designs will require an

[10] "Managing Critical Isotopes: Stewardship of Lithium-7 Is Needed to Ensure a Stable Supply," U.S. GAO, n.d., https://www.gao.gov/products/gao-13-716.

expansion of existing supply chains in order to build and operate them. For example, the amount of enriched Li^7 needed for current PWRs is very small compared to the amount that some have estimated will be needed for molten salt designs that are currently undergoing development. These estimates put the amount required between 21 and 56 metric tons per GWe capacity, assuming that FLiBe molten salt is used[11]. While this quantity of lithium is not in itself large, it is a very large amount of Li^7. Similarly, graphite will be required in molten salt and high-temperature gas reactor designs. Like steel, it must be manufactured to a set standard to withstand the in-core conditions and meet regulatory requirements. It is not produced domestically, and the US has 100% net import reliance. The top three producers are China, which produces 75% of the global supply, followed by Mozambique, and Brazil**Error! Bookmark not defined.**. For nuclear applications, graphite must also be very pure, which requires processing capacity not currently available in the US. Yttrium hydride is a possible replacement for zirconium hydride as a moderator material for advanced reactors, but the US has a 100% net import reliance, and 99% of global production comes from China**Error! Bookmark not defined.**.

Table 1 provides a summary of critical materials of notable importance in current and future advanced nuclear supply chains discussed herein. The contents are based on data from the US Department of Energy, the US Geological Survey, and the International Energy Agency. Together, they create a coherent picture of critical materials used in the nuclear supply chain and the United States specifically. An expansion of domestic nuclear energy would contribute to the straining of current supply chains, and the sourcing and processing of critical material. Additionally, any disruptions have the potential to quickly become major issues that may not only affect construction but operations as well. The United States does not have the resources to satisfy its requirements for material used in nuclear energy domestically, much less across all industries. However, by evaluating where resources are located, and assessing potential trade partners from and risk and reliability standpoint, to may be possible to make the flow of goods more robust should shocks to the global system occur.

[11] Per Peterson from https://fhr.nuc.berkeley.edu/wp-content/uploads/2014/10/12-005_NE-170_Lithium-Enrichment.pdf

Table 1. Critical materials of importance in current and future nuclear supply chains.

Mineral/ Material	DoE[1]/USGS[12]/Both Critical Material	IEA ranking of kg needed per MW Produced[2]	Mass needed per electricity produced[1 2]	Percentage Import Reliance**Error! Bookmark not defined.**	Primary Import Sources**Error! Bookmark not defined.**
Chromium	Both	1st	0.15-2.190 kg/kW	80	South Africa Kazakhstan Russia
Nickel	Both	3rd	0.1-1.300 kg/kW	48	Canada Norway Finland
Copper	DoE	2nd	0.69-1.470 kg/kW	41	Chile Canada Mexico
Manganese	Both	5th	0.33-0.70 kg/kW	100	Gabon South Africa Australia
Cadmium	DoE		0.01 kg/kW	25	Australia Germany Peru
Concrete	DoE		180-560 kg/kW	21	Canada Turkey Greece
Aluminum	Both		0.02-0.04 kg/kW	54	Canada UAE Russia
Lead	DoE		0.03-0.05 kg/kW	42	Canada Mexico South Korea
Lithium	Both			Li-7: 100 Natural: 25	Li-7: Russia China Natural: Argentina Chile China
Graphite	Both			100	China Mexico Canada
Yttrium	Both		.0005 kg/kW	100	China South Korea

[12] "U.S. Geological Survey Releases 2022 List of Critical Minerals | U.S. Geological Survey," n.d., https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals.

					Japan
Europium	USGS			N/A	N/A
Samarium	DoE			N/A	N/A
Silver	DoE		0.01 kg/kW	69	Mexico Canada Poland
Indium	Both		0.01 kg/kW	100	China South Korea
Hafnium	Both		.0005 kg/kW	N/A	Germany France China
Zirconium	Both		0.20-0.40 kg/kW	25	South Africa Senegal Australia
Tantalum	USGS			100	China Germany Australia
Holmium	USGS			N/A	N/A
Niobium	Both			100	Brazil