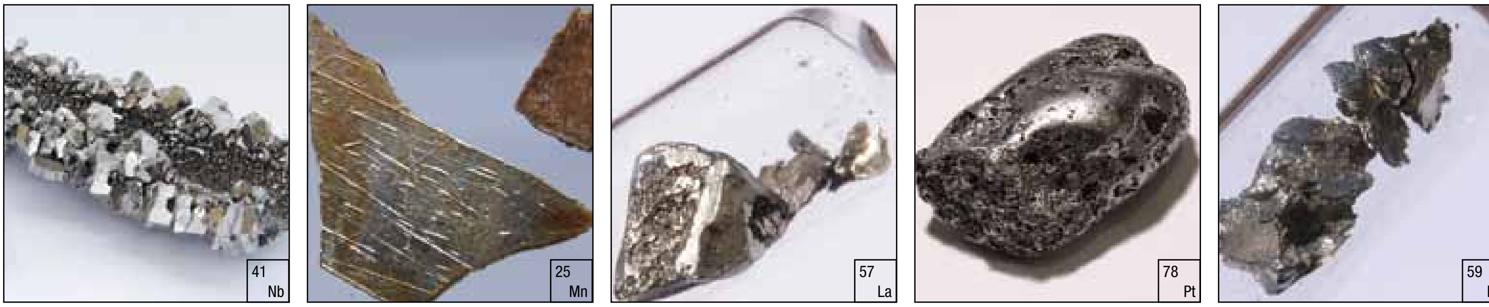


Recent government reports address issues and tactics related to scarce and critical raw materials.

(Credit: Mn image-Images of Elements; others– Wikipedia.)

Issues of scarce materials in the United States

Stephen W. Freiman and Lynnette D. Madsen

Government and the private sector can take steps to address scarcity of critical materials for manufacturing of ceramic materials.

Shortages of rare earth minerals is a visible and important issue for the economy of the United States as well as national security. Potential shortages loom, too, for other minerals. This article addresses current issues regarding the scarcity of some minerals, particularly those of important for producing engineered ceramics. We will introduce the concept of a "criticality matrix," as described in a recent National Research Council report, and we summarize current and potential future activities aimed at relieving these shortages.

The availability of raw materials is crucial to the production of advanced products in numerous areas of the economy, e.g., electronics, aerospace, automotive and is equally important to national security. As an example, the number of elements necessary for the manufacture of computer chips expanded from 11 in the 1980s to potentially 59 elements today.

The automotive industry provides another good example of the expanded range of minerals needed for today's high-performance and energy-efficient vehicles. Nearly 100 years ago, Henry Ford introduced vanadium into the steel used in the Model T to strengthen the material and reduce the weight of the car. Today's automobiles include many more functionalities than their predecessors, containing at least 39 minerals, some of which are becoming increasingly difficult to acquire. Of particular importance to the automotive sector are the platinum group metals (palladium, platinum and rhodium), which are crucial for the operation of catalytic converters. Lithium and several of the rare-earth elements are necessary for rechargeable batteries in electric and hybrid vehicles. Other important products requiring the use of potentially scarce minerals include cellular telephones (tantalum), liquid crystal displays (indium), energy-efficient lighting (rare earths), wind turbines (rare earths) and photovoltaic cells (selenium, tellurium, indium).

At one time, the US was relatively self-sufficient with respect to almost all necessary minerals. However, most of the raw materials that are used today in this country are acquired from outside sources, some of which are wholly reliable.

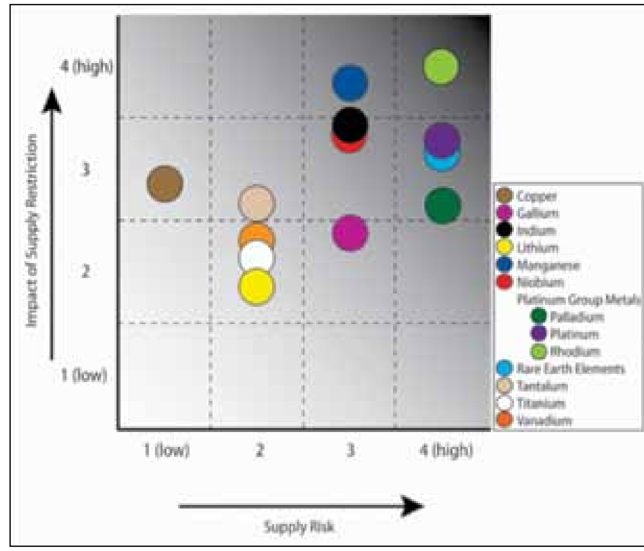
In most cases availability from foreign sources is not an issue. Normal trade relationships are in place, and availability of the material at market prices is assured. However, when one source dominates the market and there is political or social discord as well as competing needs, acquisition of the necessary minerals becomes problematic. The difficulty in obtaining certain raw materials has raised concern in the US within the government and private sector of how possible shortages of crucial starting materials could affect the manufacture of key components and national security.

The scarcity of raw materials and its impact on ceramic research and manufacturing was the primary topic at the September 2011 meeting of the Interagency Coordinating Committee on Ceramics Research and Development. This paper discusses the issues behind the scarcities and the measures available to assure that products using scarce materials can continue to be manufactured at reasonable costs.

Scarcity and criticality

A National Research Council report entitled, "Minerals, Critical Minerals, and the U.S. Economy,"[1] states that the availability of the minerals needed for the US economy can be ascribed to five factors:

- Geologic (existence and prevalence of mineral resources);
- Technical (extraction and processing of the mineral);
- Environmental (safety of mineral processing in terms of the population at large and the environment and the safety of workers);
- Political (governmental policy's effect on access); and
- Economic (viability of minerals in terms of the cost that users can and will pay).



(Credit: National Research Council; NAtional Academics Press.)

Figure 1. Criticality Matrix showing the 11 minerals examined by the NRC panel.[1]

Criticality may be defined as when the loss, reduced access to, or significant cost increase of a mineral or mineral product, causes a serious disruption in manufacturing, reduction in performance, or unacceptable price increase of a manufactured product. Although the above report focused on the commercial aspects of mineral availability, a parallel study discussed the potential impact of raw material shortages on the US military.[2]

One of the primary points made in the critical materials report is how to identify when a mineral becomes critical. The NRC committee suggested a "criticality matrix" (Figure 1). The abscissa is the risk of a supply disruption. The ordinate is the impact of a supply restriction on manufacturing and production, i.e., how important is the application. A major point made in the NRC report is that criticality is not a simple yes or no. Rather it is a continuous function of supply risk and impact. Criticality also is time dependent: What is not critical today, may be tomorrow, depending on new applications, changes in political climate, etc.

The NRC panel used a number of minerals as examples, also shown in Figure 1. Their placement in the matrix was based on the judgment of the committee.

Of the 11 minerals chosen as examples, the platinum group metals, rare earths, indium, manganese, and niobium were determined to be critical. The applications in which each of these were needed, e.g., catalytic converters, electronics, batteries and liquid crystal displays, were viewed as extremely important. The importance of these applications coupled with the difficulty in finding appropriate substitutes, and the judged risk of supply, placed them in the critical portion of the matrix.

This NRC report also states that three time intervals should be considered when evaluating criticality. In the short term—months to a few years—mineral markets are primarily influenced by unexpected changes in mineral demands, e.g., the Chinese industrial growth and demand. In the medium term—a few to 10 years—mineral users can make substitutions and bring new production facilities on line. In the long term—more than 10 years—producers can invest in innovative activities in mineral exploration, mineral processing, product design and recycling.

Today, any discussion of scarce materials usually begins with rare earths: scandium, yttrium and the lanthanides series. There is significant concern about the availability of various members of this group for commercial and national security interests. The unique properties of rare earths are based on their *f*-shell electron structures, impor-

Table 1. Applications for rare-earth elements

Element	Uses
Mixed rare-earth oxide (mischmetal)	Polishing compounds, capacitors, steel refining
Lanthanum	Nickel-metal hydride batteries, lenses, capacitors, heavy-metal fluoride glasses, petroleum cracking catalysts
Cerium	Automotive emission catalysts, glass-polishing media, UV light absorber, stabilizer for zirconia
Praseodymium	Additive to NdFeB magnets, zirconia structural ceramics, welders goggles, X-ray tomography
Neodymium	Magnets, lasers, glass-coloring agent, capacitors
Samarium	Magnets, lasers
Europium	TV phosphors, light-emitting diodes, X-ray tomography
Gadolinium	Phosphors, rf communication (phase shifters, tuners, filters), optical lenses, neutron absorbers
Terbium	Green phosphors, LEDs, magnetostrictive alloy (Terfenol-D)
Dysprosium	Additive to magnets, phosphors, Terfenol-D
Holmium	Nuclear control rods, magnets
Erbium	Fiber optic amplifier, glass colorant, synthetic gems
Thulium	X-ray intensifying screens, metal halide lamps
Ytterbium	Optical lenses, pressure sensors
Lutetium	Scintillation detectors, optical lenses
Yttrium	Sintering aid for silicon nitride, superconductors, optical lenses, metal-alloying agent, laser host, fluorescent lamps

tant for a number of applications, e.g., high-strength magnets. It is the higher atomic number rare earths (termed heavy and often given the acronym HREE) that have the lower-grade ore and greatest usage in key applications, such as magnets, catalysts and phosphors, that are the more important.

Rare earths are not rare in the earth's crust compared with many other minerals, e.g., gold, platinum and palladium. However, they are distributed in such a way that extraction and processing can be difficult and expensive. In addition, the distribution of light and heavy atomic weight elements is critically dependent on the source and chemistry of the ore from which they are extracted. According to Gschneidner,[3] at current production rates, known rare earth supplies should last for 700 years. Gschneidner also points out that with a 10-percent growth rate in use (see footnote), the known availability will be depleted in less than 70 years. At this time, rare earths have become critical because China, the major source and producer, has cut back on its exports and threatens further restriction in the supply.

Rare earths exist in sufficient abundance (ore grade and volume) worldwide. However, many factors are involved in obtaining the refined elements:

- The ratio of the light to heavy rare earths differs substantially among locations.
- The ease of processing, i.e., in terms of extracting a particular rare earth element from the ore and accompanying elements can differ from one ore source to another, leading to significant variations in the cost of processing.
- Some rare-earth-containing ores contain substantial radioactive byproducts, such as thorium, which can accumulate in the tailings after production of the primary material. These tailings must be disposed of in a safe manner.
- The price of rare earths coupled with the cost of production determines the extent to which new mines are sought and processing facilities constructed. There is a significant time lag—up to five years—between the discovery of new sources of rare earths and the delivery of finished materials.

Impact of the scarcity of rare earths

Perhaps the most important use of rare earths is in high-strength magnets. Neodymium-iron-boron and samarium-cobalt are the two most prevalent compositions. NIB is the preferred composition because of its superior magnetic properties. In terms of products, the automobile contains the largest quantity of rare earths, as magnets and catalysts.

Dysprosium is frequently substituted for 6 percent of neodymium, because it enhances the magnetic properties of the alloy and reduces its corrosion susceptibility. Portable disc drives depend for their performance on rare-earth magnets.

Europium is a critical element used as the red phosphor in cathode-ray tubes and liquid crystal displays. To date, no substitute for europium has been found for this application. Erbium is an important component for laser repeaters for maintaining the strength of signals in fiber-optic cables. Rare earths are also used as catalysts and more recently in high-efficiency lighting.

Table 1 provides more detail into the applications where rare earths play a significant role.

Impact of other scarce minerals

Other elements can be considered to be critical or near-critical. Some shortages occur because they are mined only as secondary products to other minerals:

– Indium (lighting applications) a byproduct of zinc production;

– Gallium (solar cells and photovoltaics, and GaAs for integrated circuits), a byproduct of bauxite mining, almost wholly obtained from foreign sources;

– Cobalt (additive in rechargeable batteries and fuel cells), a byproduct of nickel and copper production;

– Tellurium (semiconducting products, e.g., CdTe), dependent on copper mining; and Rhenium (component of many high-temperature alloys important to national security), a byproduct of special copper ore mining.

Challenges in a world with limited resources

National security

Element shortages present national security and economy problems. The NRC report on the National Stockpile, "Managing Materials for a 21^{st} Century

In part as a result of the concern over rare shortages, mining of new ore began at Molycorp's facilities in 2011.[4] Most of the anticipated production has been spoken for and it is accelerating both the modernization and expansion of their processing plant in California. In addition, Molycorp has been granted authorization to commence exploratory drilling for heavy rare earths.[5] Preliminary exploration at the site has shown rare earth mineralization with an average ore grade of approximately four percent and a relatively high percentage of heavy rare earths.

Military"[2] discusses issues relative to defense needs for potentially scarce materials. The report recommends establishing a new system for managing the supply of materials for national defense. It also recommended that the system include an ongoing analytic process to identify materials as part of an integrated and flexible policy framework. The report further recommended that the federal government improve systems for gathering minerals data and information.

Congress recently addressed the issue of criticality in the fiscal year 2011 National Defense Authorization Act.[6] In this document strategic materials are defined as "material essential for military equipment, unique in the function it performs, and for which there are no viable alternatives."

According to a recent a Congressional Research Service Report to Congress,[7] the US Department of Defense faces serious challenges in the acquisition of a number of elements used in defense applications. These include actuators in missile guidance systems, disk drive motors, lasers for mine detection, satellite communication systems, sonar and optical equipment.

Energy

Clean energy production depends heavily on the availability of a number of scarce elements (Table 2).[8] The Department of Energy recently has begun funding research efforts (with total funding to date of $156M) under the Advanced Research Projects Agency Energy program, REACT (Rare Earth Alternatives in Critical Technologies).[9] Its goal is to fund early-stage technology alternatives that reduce or eliminate the dependence on rare-earth materials by developing substitutes in key areas: electric vehicle motors and wind generators.

Workforce education

One of the other significant issues that can exacerbate the mineral shortage problem is the lack of trained mining and mineral-processing personnel.[1] In the area of rare earths alone, the decline in employment in the US during recent years was approximately 25,000 to 1,500.[10] This reduction reflects the alteration in mining activity in the US. However, as mines open and re-open, there will be a concomitant increased need for qualified personnel with roughly one-in-six being college educated.[11]

Table 2 Examples of scarce elements used in clean energy applications (courtesy of US Department of Energy)

Application	Component	Elements
Wind energy	Turbines	Neodymium, dysprosium
Vehicles	Motors	Neodymium, dysprosium
	Lithium-ion batteries	Lithium, cobalt
	Nickel-metal hydride batteries	Cerium, lanthanum, Neodymium, praseodymium, cobalt
Photovoltaics	Copper indium gallium (di)selenide films	Indium, gallium
	CdTe Films	Tellurium
Lighting	Phosphors	Yttrium, cerium, lanthanum, europium, terbium

In terms of mineral exploration (and geosciences in general), there is an increasing demographically driven gap resulting in a shortfall between the rate of retirement of an aging workforce and the rate of geology-degree earners. In addition, mining departments in engineering schools in the US have declined significantly in recent decades. At present, there are few universities that have maintained their mining engineering programs (with accredited curricula).[11]

Increasingly, there is a need for graduates who have an appreciation of one or more areas related to their area of specialization. NSF recently funded a center to improve and integrate geosciences across other disciplines.[12,13] Some universities are taking a proactive approach to ensure that students develop a broader perspective. For example, in the Forum Scientum program at Linköping University,[14] students are networked in complementary areas. The renewed interest in the US in sourcing rare-earth and other critical elements should lead to a greater demand for more geologists and geoscientists who have an interest in minerals and knowledge of economics.

Will the current interest in this area lead to greater enrollment of students? Certainly training the next generation of scientists and engineers to design sustainability into manufacturing will be important. In this area of sustainability one faculty member has developed an undergraduate course on scarce mineral-based and critical materials.[15] The course stresses the interrelationships between material availability, technical goals and economics. The concept of strategic recycling, including design for recycling and waste stream management is included. It is mostly taught from current literature, which allows for the relative comparisons among approaches in different regions of the world.

As one moves higher up the value-added chain, the more professionals are needed. In addition to mining engineers, beneficiation experts; geoscientists; chemical, materials and industrial engineers; material scientists; and chemists are needed for further processing of elements and product development and recycling. One NSF mechanism for training university students is the Research Experiences for Undergraduates Program.[16] At this time, there are more than 600 active REU sites. Fifteen percent of these sites have co-funding from the DOD. Several of the existing REU sites have a focus on sustainability.

Environment: Zero waste and re-use

Another potential route to increasing the supply of scarce elements is recycling, or what has been called "urban mining." Korea and Japan have begun programs toward this end.[17] The only metals being recovered on a large scale in Japan are copper, gold and indium.

For success, such recycling programs must be made economically viable.

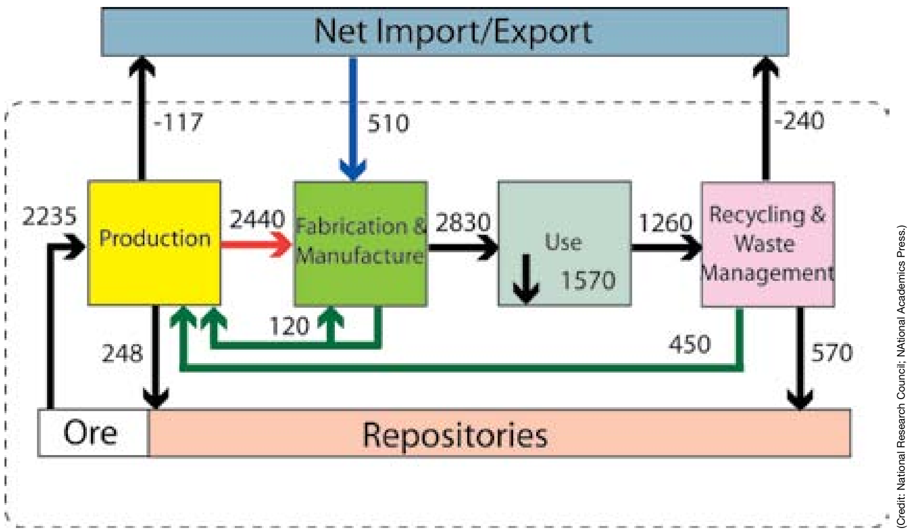


Figure 2. Example of Life Cycle Analysis for copper showing the balance of flows of materials. units are 1000 metric tons.[1]

Devices must be designed and engineered to permit elemental separation after their useful lifetime. A step toward recycling involves the study of "stocks and flows." Such a study involves determining where all sources of a particular element exist, and where stores of the element are present in applications or in waste (Figure 2).

There is interest in the engineering community in mining from industrial wastes as well as from initial sources. One such example is an NSF-supported study which has the objective to develop advanced technologies to recycle and process effluents disposed from aluminum manufacturing.[18] NSF also has helped the Worcester Polytechnic Institute[19] and Colorado School of Mines[20] to establish the Center for Resource Recovery and Recycling.[21]

Role of materials research

There are a number of additional possible ways in which the private sector and the government are addressing these potential shortages. One of the obvious choices is to find suitable replacements for the critical elements. In the case of rare earths, this is not easy. The unique magnetic properties of the rare-earth series occur as a result of the *f*-electron shell. Finding other elements, or combinations of elements, that can duplicate the properties of rare earths, while maintaining the same efficiencies, is challenging. However, through the science of nanotechnology, it may be possible to reduce the quantity of rare earths in each material application.

One NSF-supported project focuses on achieving a better understanding of tellurium isotopes.[22] Tellurium is used primarily in industry to form copper, lead and iron alloys and more machinable stainless steel. As well, it has a wide variety of uses (ceramics, glass fiber, vulcanized rubber, electronics industry) and with CdTe becomes a primary material in solar panels.

To date, the Ceramics Program at NSF has only a few projects that focus on alternatives or approaches that minimize the use of hazardous or scarce minerals or those that enable recycling of specific elements. One exception is the search for lead-free piezoelectrics; use of lead is restricted im many countries because of its toxicity.

Additional on-going and planned US government activities

One of the NSF focus areas for Fiscal Year 2012 is Science, Engineering and Education for Sustainability.[23,24] There are many activities and opportunities under SEES that capitalize on NSF's unique role in helping society address the challenges of achieving sustainability. The mission of SEES is "to advance science, engineering and education to inform the societal actions needed for environmental and economic sustainability and sustainable human well-being." It is a cross-cutting NSF-wide investment area that will include support for interdisciplinary research and education.

In addition to REACT, DOE has several Energy Innovation Hubs, such as the Batteries and Energy Storage Energy Innovation Hub, that complement the usual funding mechanisms. Hubs include many investigators spanning multiple science and engineering disciplines, such as energy policy, economics and market analysis. These efforts are funded at ~$25M per year for an initial period of five years.[25]

Recently, workshops have been held on scarce minerals that have examined the issues and impact on scientific research and product development. As well, DOE has commissioned a report on rare earths[26] outlining a strategy, and NSF has created a website that lists many recent meetings and reports on this topic.[27] This topic also has garnered attention in Congress and the Executive Branch. For the latter, several interagency working groups (focused on different aspects) are examining the best paths forward. Included in the charge is examining market forces, addressing supply diversification, securing domestic supply chains, providing information to inform government and industry decision-making, addressing environmental concerns and ensuring a prepared workforce.

The Materials Genome Initiative for Global Competitiveness[28]—introduced in 2011—has the potential to provide a better understanding between the elements used in a material and their subsequent properties. This effort should also accelerate the process of building components composed of fewer scarce elements.

Future directions

Steps that can be or are being undertaken by the private sector and government to help alleviate the problem. They are listed starting with the acquisition and recycling of scarce minerals through product design. An additional overarching issue in this area and overall in science, technology, engineering and mathematics fields is attracting and cultivating an educated workforce.

Acquisition

- Identify critical elements/minerals and estimate future needs.
- Support efforts to collect data on sourcing of critical elements.
- Improve data exchange and analysis mechanisms and techniques.
- Support development of new geophysical modeling for discovery of new scarce mineral sources.
- Continue developing trade agreements with foreign sources to minimize supply disruption risk.
- Make recycling and recovery of scarce elements economically viable.
- Address social aspects of extensive recycling efforts.

Beneficiation

- Develop efficient, green extraction and processing methods that reduce energy, water and organic solvent use.
- Establish metrics.
- Develop new chemistry to convert nonpetroleum-based sources of organic molecules to feedstock chemicals.

Product development

- Explore nanotechnology to reduce amounts of an element needed in specific applications.
- Develop earth-abundant substitutes for critical elements; optimize materials design from the start.
- Design for recycling.
- Deepen understanding of physics governing structure–property relationship.

Workforce development

- Increase incentives to attract a diverse set of students to pursue relevant disciplines.
- Train new scientists and engineers in sustainable manufacturing.
- Expand traditional university curriculum and/or explore approaches to broadening student knowledge base.

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Disclaimer

Any opinion, finding and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF.

About the authors

Stephen W. Freiman is president of Freiman Consulting, Potomac, Md. Lynnette D. Madsen is a program director in the Division of Materials Research, US National Science Foundation, Arlington, Va. Contact: steve.freiman @comcast.net.

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