



Minerals, Critical Minerals, and the U.S. Economy

Committee on Critical Mineral Impacts of the U.S. Economy, Committee on Earth Resources, National Research Council

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CHAPTER 6

Conclusions and Recommendations

Minerals, or more specifically the mineral products derived from them, are essential to the functioning of modern processes and products. Some minerals are more essential than others, in the sense that they have few if any substitutes capable of providing similar functionality at similar costs.

The availability of these minerals is a function of geologic, technical, environmental and social, political, and economic factors. Some minerals are more prone than others to disruptive restrictions in supply.

It is this combination of importance in use and supply risk, and specifically the potential that an important mineral may be subject to supply restrictions, that motivated this study. The committee was charged to carry out a number of specific tasks identified in Chapter 1:

1. Identify the critical minerals and mineral products that are essential for industry and emerging technologies in the domestic economy.
2. Assess the trends in the sources and production status of these critical minerals and mineral products worldwide.
3. Examine actual or potential constraints, including but not limited to geologic, technologic, economic, and political issues, on the availability of these minerals and mineral products for domestic applications.
4. Identify the impacts of disruptions in supply of critical minerals and mineral products on the domestic workforce and economy.

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5. Describe and evaluate the current mineral and mineral product databases and other sources of information available for decision making on mineral policy issues.
6. Identify types of information and possible research initiatives that will enhance understanding of critical minerals and mineral products in a global context.

Chapters 2 through 5 have examined the various dimensions of the overall task, and each chapter concluded with principal findings. This chapter presents the committee's principal conclusions, drawing on each previous chapter's findings, and summarizes the committee's recommendations following from these conclusions. Throughout its examination of these issues, the committee found it essential to consider minerals, and critical minerals, in the context of a global mineral and material cycle—from mineral ores at the mine to metallic and nonmetallic minerals in potentially recyclable materials and products.

The committee established parameters regarding a mineral's *importance in use* and *availability* (supply risk) to apply the criticality matrix to 11 minerals or mineral groups: copper, gallium, indium, lithium, manganese, niobium, platinum group metals (PGMs), rare earth elements (REs), tantalum, titanium, and vanadium. The committee did not have the time or resources to evaluate all potentially critical minerals. Instead, the committee selected the minerals identified above on the basis of two considerations. First, the set of minerals the committee examined had to illustrate the range of circumstances that the matrix methodology accommodates and considers. For example, in its selection of the minerals examined in this report, the committee considered minerals used in large quantities throughout the economy in traditional applications and others used in limited quantities in a small number of (often emerging) applications, minerals produced largely as by-products, and other minerals for which recycling of scrap is an important source of supply. Second, the set of minerals had to consist of those that, in the professional judgment of committee members, would likely be included in a more comprehensive assessment of all potentially critical minerals. The committee used a combination of quantitative

measures and expert (qualitative) judgment in implementing the matrix methodology.

CONCLUSIONS

Defining Criticality

The committee concludes that **all minerals and mineral products could be or could become critical to some degree, depending on their importance and availability**—in the sense that the chemical and physical properties they provide are essential to a specific product or use or more broadly, that specific minerals are an essential input for a national priority (for example, national defense) or for an industry, or may be important (or have the potential to become important) to a region or the nation as a whole. Materials derived from minerals are essential to the performance of nearly all products and services we take for granted—cellular telephones, automobiles, home appliances, computers and other electronic products, and aircraft, for example. The degree of a mineral's importance can vary considerably over time as technologies and the economy evolve and change.

The committee also concludes, however, that more useful **from the federal perspective is the concept of a critical mineral as one that is both essential in use and subject to supply restriction**. In other words, the key determinants of criticality here are importance in use and availability. Based on these determinants, the committee developed a methodology—a 'criticality matrix'—for assessing the criticality of specific minerals and identified the information requirements for implementing this methodology. The matrix has two dimensions. The first (vertical axis) represents the degree of importance of a mineral or, equivalently, the impact of a supply restriction. The second dimension (horizontal axis) represents the degree of supply risk or the risk of a supply restriction.

This methodology emphasizes that criticality is a relative concept in that minerals are more or less critical, rather than critical or not critical. At any time, and for any organization or nation, some minerals will be more critical than others. Over time, **the criticality of a specific mineral**

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can and likely will change as production technologies evolve and new products are developed.

Furthermore, the committee concludes that in implementing the methodology to assess criticality, **it is important to distinguish among three time or adjustment periods.** In the *short term* (period of a few months to a few years), mineral markets and in turn prices are influenced primarily by unexpected changes in mineral demand, such as the largely unanticipated increase in Chinese mineral demand over the last several years, and by unexpected shortfalls in production due to technical or other problems at existing mines and production facilities. In the short term, from the perspective of a mineral market as a whole, mineral users and producers are constrained by their existing production capacity, and therefore, unexpected changes in demand or supply are reflected largely in inventories held by producers, users, and commodity exchanges.

In the *medium term* (a few years, but no more than about a decade), markets respond to short-term developments but still in a relatively limited manner; for example, if a mineral's availability has become restricted, mineral users make any easy substitution for this mineral, and mineral producers bring into production any easy-to-develop, higher-cost sources of the restricted mineral (e.g., higher-cost scrap that previously was not recycled; and higher-cost, known but underdeveloped mineral deposits). In the medium term, mineral users and producers are essentially limited by existing technologies and known primary and secondary mineral resources.

Over the *long term* (roughly a decade or more), mineral users and producers can respond more significantly to changes in mineral availability through conscious decisions about whether and to what degree to invest in innovative activities in mineral exploration, mine development, mineral processing, product design and manufacturing, and recycling technology and policy.

Understanding Importance in Use or the Impact of a Supply Restriction

Users demand minerals and mineral attributes for the functionality they provide—their chemical and physical properties in specific applications

such as strength, corrosion resistance, electrical conductivity, low density, and so on. As noted at the beginning of this chapter, some minerals are more essential than others in the sense that they have few if any substitutes capable of providing similar functionality at similar costs. **The greater the difficulty, expense, or time it takes for material substitution to occur, the more critical a mineral is to a specific application or product—or analogously, the greater is the impact of a supply restriction.**

The impact of a specific supply restriction, in other words, depends on the nature of the restriction. A supply restriction can occur in two general forms. First, demand can increase and outstrip existing production capacity (a demand shock). Second, in what normally would be considered a disruption, a material that previously was available becomes unavailable (a supply shock). In either case, it is possible that a mineral or mineral product becomes physically unavailable; in this situation, the product a user makes cannot be manufactured, sold, and then used by the prospective purchaser. More typically, however, a mineral or mineral product remains physically available, but at a higher price. In this situation, supply will be reallocated to those users willing to pay more for a mineral or mineral product and away from lower-valued uses.

The specific impact of a supply restriction will depend on circumstances: Is the mineral physically unavailable, or have prices increased? If prices rise, by how much? How flexible or inflexible is demand (that is, how easy or difficult is it to substitute for the restricted mineral)? Finally, time is important. In the short term, mineral users will be relatively limited in the degree to which they can adjust to physical unavailability or higher prices for a mineral or mineral product. Users are constrained by the flexibility of their production processes that use minerals as inputs. Most production processes are relatively inflexible in the short term. A facility that manufactures aluminum cans, for example, cannot immediately reduce the amount of aluminum it uses per can or convert itself into glass bottle making facility. In the medium term, users have somewhat more flexibility. An aluminum can-making facility might be able to invest in existing technology that uses less aluminum per can than its facility currently requires. Alternatively, it might decide to become a glass bottle-making facility. Over

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the long term, users of minerals and mineral products will be relatively most flexible to respond to a supply restriction. There is time for a facility that manufactures aluminum cans to innovate and develop a process for using less aluminum per can than previously.

In any of these adjustment periods, the types of possible effects include impacts on:

- *Domestic production of minerals and mineral products:* there may be opportunities for increased domestic production of the mineral or mineral product whose supply has been restricted (higher-cost but previously uneconomic primary or secondary production).
- *Domestic users of minerals or mineral products (typically producers of semifabricated products and manufacturers of final products):*
 - Lost production due to lack of availability or higher costs (use will be concentrated in higher-valued uses of a mineral or mineral product);
 - Higher costs of production, which producers may or may not be able to pass along to consumers;
 - Slower growth than otherwise in emerging-use industries;
 - Less employment than otherwise in industries using minerals and mineral products as inputs;
 - Ultimately lower value added in those sectors using minerals and mineral products, and lower gross domestic product (GDP), although the impact on GDP of a supply disruption for any single mineral or mineral product will be small from the perspective of the national economy;
 - Higher costs or reduced availability of products related to national defense.
- *Domestic purchasers of goods containing minerals and mineral products:* there may be fewer purchases or more expensive purchases because goods have become more expensive (in either case, purchasers are worse off than previously).

The committee did not attempt to quantify these effects. To do so would have required detailed and separate economic impact analyses for each specific circumstance, and the committee was not constituted with sufficient expertise to carry out this type of quantitative analysis. However, the committee notes that the largest impacts on national employment and GDP would come from supply restrictions on minerals and mineral products used in large quantities; of the minerals the committee examined using its criticality methodology, copper falls into this category, even though copper did not qualify as critical in the committee's eyes because its supply risk is low. Other minerals that the committee believes would be evaluated similarly include iron ore, aluminum, and aggregates.

Understanding Availability and Supply Risk

Fundamentally, minerals are a primary resource in that we obtain them from the Earth's crust. At any point in time, however, minerals—or more precisely the mineral products obtained from them—are available as secondary resources through recycling of obsolete or discarded products and materials. Finally, from the perspective of a nation, mineral products are available as tertiary resources embodied in imported products or imported scrap. The U.S. economy obtains minerals and mineral products in all three forms—primary, secondary, and tertiary. Although the United States has been and remains an important producer of primary and secondary minerals, it also relies on imports for a number of primary and tertiary minerals.

For primary production worldwide and in the United States, mineral exploration, mining, and mineral processing are sectors whose fortunes change significantly from year to year because of the strong link between mineral demand and economic growth. In periods of especially strong economic growth, mineral use in general expands more quickly than production capacity, tending to drive up mineral prices, whereas in periods of slower growth or recession, mineral use tends to grow more slowly than production capacity and prices tend to fall. Given the fragility of the balance between demand and supply, mineral prices tend to swing significantly

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from one year to another. Since early in this decade, the mineral sector overall has experienced an extended boom (and relatively high mineral prices) due to a number of factors, including unexpectedly large increases in mineral demand in China and some other countries and unexpected interruptions in production at a number of mines due to technical problems and other factors.

The level and location of mine production today depend on the level and location of mineral exploration in the past. The level of exploration tends to follow changes in mineral prices, but usually with a short time lag. The composition of exploration activity varies with mineral prices. In recent years during a period of relatively high mineral prices, exploration by small exploration companies (termed “juniors”) in riskier and more remote locations has increased proportionately more than exploration by larger and more established mining companies. Conversely, when mineral prices fall, exploration by junior companies tends to fall proportionately more than that by larger companies, resulting in relatively less exploration in remote locations and more exploration in proximity to existing mines. The geographic location of exploration and mining also evolves over time. In recent years, relatively more exploration and mining has occurred outside the established areas of Australia, Canada, and the United States.

Turning from primary to secondary production, recycling tends to be concentrated close to semifabrication and metal manufacturing facilities and close to urban centers to take advantage of the creation of scrap when buildings are demolished and products are discarded. As a result, most metal recycling occurs in industrialized economies where the majority of metal use historically has occurred. Nevertheless, a significant amount of recycling occurs in developing economies, where perhaps a larger percentage of the available scrap is actually recycled than in industrialized economies. Given the long-term trend of increasing mineral use and low rates of recycling, recycled materials cannot presently meet a large proportion of demand for most materials. Over time, as products used in developing economies become available for recycling, we can expect scrap flows to increase and the location of recycling to become more geographically diverse than at present.

In considering supply risk and implementing the matrix methodology, as noted above, the committee found it essential to distinguish between short- and medium-term availability of minerals and mineral products, on the one hand, and long-term availability, on the other. **In the short and medium term, there may be significant restrictions to supply for at least five reasons.** First, **demand may increase significantly**, and if production already is occurring at close to capacity, then either a mineral may become physically unavailable or, more likely, its price will rise significantly—demand can increase more quickly than production capacity can respond. Second, an increase in demand due to growth in new applications of a mineral may be especially restrictive or disruptive if preexisting uses were small relative to the new use (**thin markets**). Third, supply may be prone to restriction if **production is concentrated**; if concentrated in a small number of mines, supply may be prone to restriction if unexpected technical or labor problems occur at a mine; if concentrated in the hands of a small number of companies, supply may be prone to restriction by opportunistic behavior of companies with market power; if concentrated in the hands of a small number of producing countries, supply may be prone to restriction due to political decisions in the producing country. Fourth, if **mine production comes predominantly in the form of by-product production**, then the output over the short term (and perhaps even longer) may be insensitive to changes in market conditions for the by-product because the output of a by-product is largely a function of market conditions for the main product. Finally, the **lack of available old scrap for recycling or of the infrastructure required for recycling** makes a market more prone to supply restriction than otherwise.

An additional factor, import dependence, often is cited as an indicator of vulnerable supply and has carried the implication that imported supply may be less secure than domestic supply. The committee concludes that **import dependence by itself is not a useful indicator of supply risk**. In fact, import reliance may be good for the U.S. economy if an imported mineral has a lower cost than the domestic alternative. Rather, for imports to be vulnerable to supply restriction, some other factor must be present that makes them vulnerable to disruption—for example, supply is concentrated

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in one or a small number of exporting nations with high political risk or in a nation with such significant growth in internal demand that formerly exported minerals may be redirected toward internal, domestic use. However, imports may be no less secure than domestic supply if they come from a diverse set of countries or firms or if they represent intracompany transfers within the vertical chain of a firm (for example, imported metal concentrate to be smelted and refined at a company's domestic processing facilities).

Over the longer term, the availability of minerals and mineral products is largely a function of investment and the various factors that influence the level of investment and its geographic allocation and success. An important investment is that in education and research, and the committee suggests that the **long-term availability of minerals and mineral products also requires continued investment in mineral education and research.**

Education and research contribute to determining long-term mineral availability for both primary and secondary resources in all of their dimensions. For primary resources, the first important dimension is geologic availability (in what quantities, concentrations, and mineralogical forms does a mineral exist in Earth's crust?). Education and research of course do not determine whether and in what form a mineral occurs in Earth's crust; rather education and research determine our *knowledge* of Earth's crust. The second determinant is technical availability (does the technology exist to extract and process the element or mineral?). Technical availability depends on investment in technological knowledge. The third determinant is environmental and social availability (can we mine and process minerals such that the consequences of these activities on local communities and on the natural environment are consistent with social preferences and requirements?). Environmental and social availability depends on investment in activities that appeal to social preferences and that develop means for carrying out mining and mineral processing in socially acceptable ways. The fourth determinant is political availability (to what extent do public policies influence mineral supply?). Political availability depends on investment in the design of public policy and on the political decisions governments make that influence the level and location of production. The fifth and

final determinant is economic availability (can we produce minerals and mineral products at prices that users are willing and able to pay?). In some sense, economic availability reflects the combined effects of the other four determinants of availability.

For secondary resources over the longer term, availability depends on four of the same above factors. Technology in the secondary resources sector is far behind that in the primary sector, and many gains are to be had by investing additional engineering time and effort. On the environmental and social front, recycling needs to occur with a greater degree of urgency, and making changes in this area is largely a social challenge. Politically, attention needs to be paid to understanding the national implications of resource scarcity, to providing the funds to better characterize the secondary resource, and to better evaluate opportunities for domestic recovery of secondary materials. Finally, it will be necessary to create economic incentives to make better use of the secondary resources now above the ground and in use, but often more costly to use at present than imported virgin material. Well-designed and competently directed research into improved recycling technologies may prove an effective tool in the reduction of our dependence on imports of critical minerals.

Implementing the Mineral Criticality Matrix

The committee applied its criticality matrix methodology to 11 minerals or mineral families it considered candidates for criticality. The committee acknowledges the existence of numerous other minerals that individuals, industrial sectors, organizations, or government officials might consider critical to their particular needs or requirements now or in the future. At a practical level, the committee did not have the resources for comprehensive analysis of all minerals using its methodology.

In evaluating these minerals or mineral families, the committee took a short- and a medium-term perspective—that is, within the next decade, what are the risks of a supply restriction, and how significant would the impact of restrictions be should they occur? Of the 11 minerals or mineral families the committee examined, **those that exhibit the highest degree**

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of criticality at present are: indium, manganese, niobium, PGMs, and REs. The committee studied PGMs and REs in some depth, while it examined indium, manganese, and niobium in a more limited manner. Each of these minerals has a slightly different story in terms of importance in use (impact of a supply restriction) and availability (supply risk), the two dimensions of criticality.

PGMs—consisting primarily of platinum, palladium, and rhodium—are essential in automotive catalysts. Palladium can partially substitute for platinum in gasoline vehicles. Palladium cannot be substituted for platinum in diesel vehicles. Rhodium has no known substitutes in the control of NO_x emissions. PGMs also are essential determinants of product quality in several industrial applications (the production of fertilizers, explosives, and petrochemicals). PGMs are mined almost exclusively in South Africa and Russia, and are typically mined as coproducts. The United States has two small PGM mines and a minor quantity of subeconomic PGM resources. Recycling occurs, primarily of spent automotive catalysts, but this amount is modest relative to annual use. The PGM market is relatively small, with annual worldwide mine production on the order of 200,000 kilograms.

REs are essential, with few if any good substitutes, in automotive catalytic converters, permanent magnets, and phosphors used in medical imaging devices, televisions, and computer monitors. The RE market is fragile because it is small—worldwide mine production in 2006 was on the order of 100,000 metric tons. U.S. manufacturers import REs predominantly from China. Very little recycling occurs. The United States has significant RE resources, but at present these resources are subeconomic.

Indium has no adequate substitutes for flat-panel displays. This use has experienced rapid growth in recent years. Worldwide mine production is small—some 500 metric tons in 2006, largely as a by-product of zinc mining and processing. The indium that U.S. manufacturers use comes primarily from China, Canada, Japan, and Russia. Very little indium is recovered through recycling.

Manganese has no satisfactory substitutes as a hardening element in various types of steel. It is not mined at present in the United States. The

majority of U.S. imports comes in the form of ore from Gabon and South Africa and ferromanganese from South Africa, China, Brazil, and France. U.S. manganese resources are subeconomic. Some manganese is recovered as a part of ferrous and nonferrous scrap recovery; almost none of this recovery is for manganese in particular but rather for the steel or other nonferrous metal of which manganese is a minor element.

Niobium is used in carbon, high-strength low-alloy (HSLA), and stainless steels. It also is used in superalloys for aircraft engines. Where substitution is technically possible, performance is sacrificed. Niobium use in HSLA steels has fallen considerably, but has increased in superalloys. Niobium is not mined in the United States, at least not in any significant quantity. U.S. users import the majority of their niobium from Brazil and to a lesser extent from Canada. The niobium market is small; estimated 2006 mine production was on the order of 60,000 metric tons. Known U.S. resources are very small and subeconomic. Significant recycling of niobium from niobium-containing steels and superalloys occurs; very little of this recycling is targeted at niobium in particular but rather for the steel or superalloy itself.

On the basis of these applications of the methodology, the committee concludes that **the criticality matrix methodology is a useful conceptual framework for evaluating a mineral's criticality in a balanced manner in a variety of circumstances that will be useful for decision makers in the public and private sectors.** Decision makers should be prepared to reevaluate a mineral's criticality whenever one of the underlying determinants of criticality changes or appears likely to change. In the short to medium term, the most likely factors to change are, first of all, demand, which could increase sharply if a new application is developed for a specific mineral and, second, the degree to which a mineral's production is concentrated in a small number of companies or countries, which in turn might be prone to opportunistic behavior. A more nuanced and quantitative version of the matrix could be established and used as part of the federal program for mineral data collection, analysis, and dissemination.

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Assessing Information and Research Needs

In the progress of this study, the committee has frequently compared the constrained scope and depth of information on minerals with the broad scope and great depth of financial information acquired and analyzed by the federal government. The usefulness of this financial information by governments, industries, and many other users suggests that an enhanced information program on minerals could be more broadly and deeply beneficial as well. The mineral information available at present is used widely but is also acknowledged to be considerably less detailed than is desirable. This is particularly the case for mineral information related to other countries, where high-quality data are essential for accurate determinations of criticality for U.S. industries and for the country as a whole.

A large number of government and nongovernmental, international, and domestic organizations collect and disseminate information and databases relevant for decision making on critical minerals and other mineral policy issues for public and private use. The consensus view of private, academic, and federal professionals is that the U.S. Geological Survey (USGS) Minerals Information Team is the most comprehensive, responsible, and responsive source of mineral information internationally, but that the quantity and depth of its data and analysis have fallen in recent years, due at least in part to reduced or static budgets and associated reductions in staff and data coverage.

In its evaluation of information and research needs, the committee concludes the following:

- **Decision makers in both the public and the private sectors need continuous, unbiased, and thorough mineral information provided through a federally funded system of information collection and dissemination.**
- **The effectiveness of a government agency or program is dependent on the agency's or program's autonomy, its level of resources, and its authority to enforce data collection.** In the committee's view, **federal information gathering for minerals at**

present does not have sufficient authority and autonomy to appropriately carry out data collection, dissemination, and analysis. In particular, the committee concludes that USGS Minerals Information Team activities are less robust than they might be, in part because it does not have status as a “principal” statistical agency.

- **More complete information needs to be collected, and more research needs to be conducted, on the full mineral life cycle.** The committee includes its specific recommendations in the following section. A common theme in these recommendations is the value of an investment in material flow accounting to better quantify stocks, flows, and uncertainty for primary, secondary, and tertiary resources.

RECOMMENDATIONS

Recognizing the dynamic nature of mineral supply and demand and of criticality, and in light of the conclusions above, the committee makes the following recommendations:

1. The federal government should enhance the types of data and information it collects, disseminates, and analyzes on minerals and mineral products, especially as these data and information relate to minerals and mineral products that are or may become critical.

In particular, more attention than at present needs to be given to those areas of the mineral life cycle that are underrepresented in current information-gathering activities, including: reserves and subeconomic resources; by-product and coproduct primary production; stocks and flows of secondary material available for recycling; in-use stocks; material flows; international trade, especially of metals and mineral products embodied in imported and exported products; and related information deemed appropriate and necessary. Enhanced mineral analysis should include periodic assessment of mineral criticality over a wider range of minerals and in

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greater depth than was possible for this committee to undertake, using the committee's methodology or some other suitable method.

2. The federal government should continue to carry out the necessary function of collecting, disseminating, and analyzing mineral data and information. The USGS Minerals Information Team, or whatever federal unit might later be assigned these responsibilities, should have greater authority and autonomy than at present. It also should have sufficient resources to carry out its mandate, which would be broader than the Minerals Information Team's current mandate if the committee's recommendations are adopted. It should establish formal mechanisms for communicating with users, government and nongovernmental organizations or institutes, and the private sector on the types and quality of data and information it collects, disseminates, and analyzes. It should be organized to have the flexibility to collect, disseminate, and analyze additional, nonbasic data and information, in consultation with users, as specific minerals and mineral products become relatively more critical over time (and vice versa).

The Energy Information Administration provides a potential model for such an agency or administrative unit. The federal government should consider whether a comparable mineral information administration would have status as a principal statistical agency and, if not, what other procedures should be investigated and implemented to give an agency with the mandate to collect mineral data and information greater autonomy and authority, as well as sufficient resources to carry out its mandate. In the globalized mineral market, it is essential that the United States has a central authority through which to conduct outreach and exchange programs on mineral data with international counterparts and to collect and harmonize data from international sources. Combined U.S. government and foreign government efforts are likely to provide the most accurate, uniform, and complete data sets of this information over time and thereby provide adequate information to all communities concerned about future global mineral or material supply and demand trends.

3. Federal agencies, including the National Science Foundation, Department of the Interior (including the USGS), Department of Defense, Department of Energy, and Department of Commerce, should develop and fund activities, including basic science and policy research, to encourage U.S. innovation in the areas of critical minerals and materials and to enhance understanding of global mineral availability and use.

Without renewed federal commitment to innovative mineral research and education, it is doubtful whether the recommended activities regarding mineral information will be sufficient for the nation to successfully anticipate and respond to possible short- to long-term restrictions in mineral markets.

The committee recommends the following additional initiatives in this regard:

- Funded support for scientific, technical, and social scientific research focusing on the entire mineral life cycle, especially those specific areas identified in Recommendation 1; and
- Cooperative programs involving academic organizations, industry, and government to enhance education and applied research.

