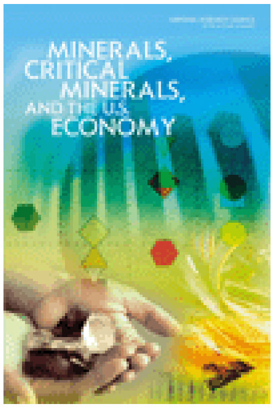

Minerals, Critical Minerals, and the U.S. Economy

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

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Summary

INTRODUCTION

The unique properties of nonfuel minerals, mineral products, metals, and alloys contribute to the provision of food, shelter, infrastructure, transportation, communications, health care, and defense. Every year more than 25,000 pounds (11.3 metric tons) of new nonfuel minerals must be provided for each person in the United States to make the items that we use every day. As our ability has advanced to produce new materials and to characterize, predict, and exploit the chemical and physical properties of nonfuel minerals, it has become possible to develop new applications that improve the technical performance, durability, and reliability of products; to deliver greater value to businesses and consumers; and to reduce environmental burdens. In the modern age, developments in materials science and engineering, mineral exploration, and processing continue to enable and support new technologies; the existence or function of common items such as cellular telephones, computers, automobiles, toothpaste, paint, or a stable electrical supply could not be possible without nonfuel minerals or mineral products and related materials. Minerals are thus fundamental inputs to the domestic economy and daily life at scales ranging from the individual consumer to entire manufacturing and engineering sectors.

Many existing and emerging technologies require nonfuel minerals that are not available in the United States. The global nature of the nonfuel mineral market has been made very evident in recent years as many emerging economies have become significant as both producers and consumers of various raw mineral products, in some cases competing for mineral feedstock directly with U.S. producers, manufacturers, and users. While foreign competition for minerals is one aspect in a range of factors affecting the supply of minerals to the U.S. economy, a high degree of import dependence for certain minerals is not in itself a reason for concern. However, import dependence can expose a range of U.S. industries to political, economic, and other risks that vary according to the particular situation. Informed planning to maintain and enhance domestic economic growth requires knowledge of potential restrictions in the supply of nonfuel minerals, as well as the strategies to mitigate the effects of those restrictions.

This study was an outgrowth of discussions during the past several years with the Committee on Earth Resources of the National Research Council (NRC) on the topic of nonfuel minerals, their availability and use in domestic applications, and their national importance in a global mineral market. The committee was concerned that the impacts of potential restrictions on the supply of nonfuel minerals to different sectors of the U.S. economy were not adequately articulated in the national discussion of natural resource use. In addition, federal responsibilities to acquire and disseminate information and conduct research on critical nonfuel minerals were not well defined in a framework that also accounts for the complete, global mineral cycle, from exploration to recycling. Positive response to the committee's formulation of a study prospectus by several federal agencies and professional organizations, including two of the study's eventual sponsors, the U.S. Geological Survey and the National Mining Association, encouraged the NRC to establish the Committee on Critical Mineral Impacts on the U.S. Economy (Appendix A); this report is the committee's response to the study's statement of task (Box S.1).

This report investigates and highlights the importance of nonfuel minerals in modern U.S. society; which minerals might be termed "critical" and why; the extent to which the availability of these minerals is subject to restriction in the short to the long term; and when considering mineral criticality, which data, information, and research are needed to aid decision makers in taking appropriate steps to mitigate restrictions in the nonfuel mineral supply. The audience for the study includes not only federal agencies, industry, and research organizations, but necessarily also the general public and decision makers.

Chapter 1 establishes the basic methodology used by the committee to determine mineral criticality in the framework of a "criticality matrix"

BOX S.1
Statement of Task

Understanding the likelihood of disruptive fluctuation in the supply of critical minerals and mineral products for domestic applications, and making decisions about policies to reduce such disruptions, requires thorough understanding of national and international mineral sources, mineral production technology, the key uses of minerals and mineral products in the United States economy, and potential impediments to the mineral supply.

This study will:

1. Identify the critical minerals and mineral products that are essential for industry and emerging technologies in the domestic economy (addressed in Chapters 1-3 and in culminating discussion in Chapter 4);
2. Assess the trends in sources and production status of these critical minerals and mineral products worldwide (addressed in Chapters 3 and 4);
3. Examine the actual or potential constraints, including but not limited to geologic, technological, economic, and political issues, on the availability of these minerals and mineral products for domestic applications (addressed in Chapters 3 and 4);
4. Identify the impacts of disruptions in supply of critical minerals and mineral products on the domestic workforce and economy (addressed in Chapter 2);
5. Describe and evaluate the current mineral and mineral product databases and other sources of mineral information available for decision making on mineral policy issues (addressed in Chapter 5); and
6. Identify types of information and possible research initiatives that will enhance understanding of critical minerals and mineral products in a global context (addressed in Chapter 5).

(Figure S.1) and establishes the concept of the "material flow" or "life-cycle" approach to assessing minerals and their criticality. Chapter 2 examines the vertical axis of the criticality matrix—the *importance of minerals in use*—through examples that demonstrate specific applications of minerals and materials in some important U.S. industrial sectors and the significance of the degree of mineral *substitutability* in these applications. Chapter 3 examines the horizontal axis of the criticality matrix—the *availability* and

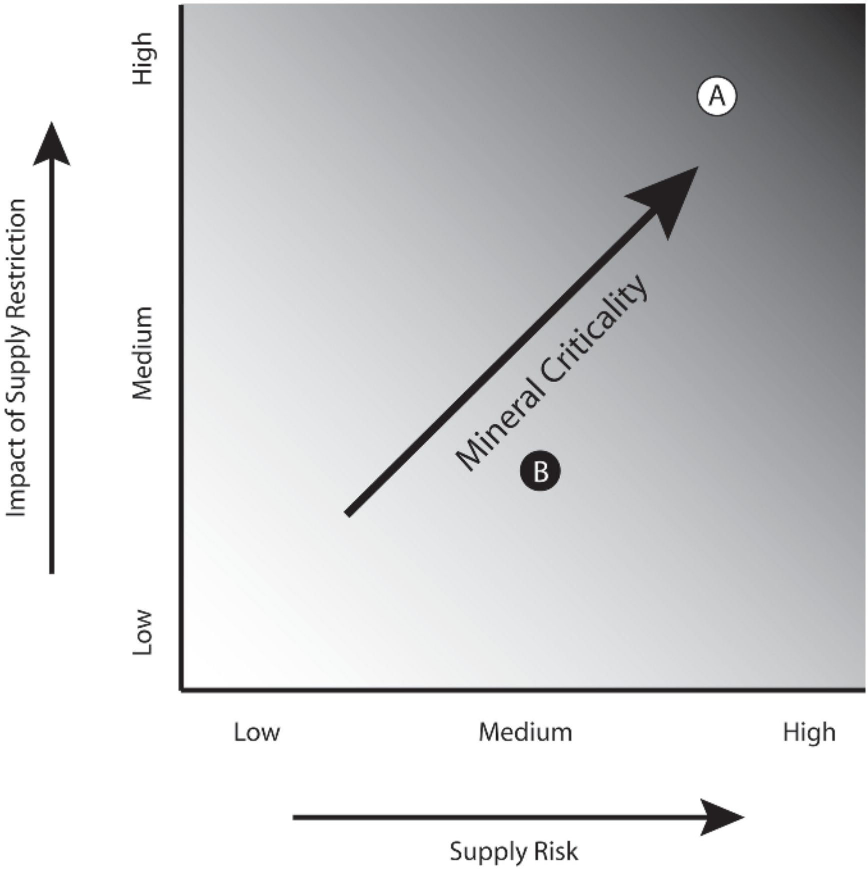

FIGURE S.1 The criticality matrix as established in this report allows evaluation of the "criticality" of a given mineral. A specific mineral or mineral product can be placed on this figure after assessing the impact of restriction on the mineral's supply should it occur (vertical axis) and the likelihood of a supply restriction (horizontal axis). The degree of criticality increases as one moves from the lower-left to the upper-right corner of the figure. In this example, mineral A is more critical than mineral B. More quantitative descriptions of the parameters used to evaluate mineral supply restrictions and their impacts are presented in this report in terms of composite scores for 11 minerals assessed in this study.

reliability of the mineral supply (supply risk)—to more completely describe the numerous factors that can affect mineral supply from short- through long-term periods. Factors affecting the availability of primary (virgin ore), secondary (e.g., scrap or recycled products), and tertiary (imported goods presently in service) mineral sources are also examined. Chapter 4 demonstrates the application of the criticality matrix methodology to evaluate mineral criticality by examining 11 mineral candidates for criticality. The minerals and their applications cross many more industry sectors than the four examined in detail in Chapter 2 and serve to underscore the ubiquitous applications for minerals in everyday life. The committee specifically examined copper, gallium, indium, lithium, manganese, niobium, platinum group metals (PGMs: platinum, palladium, rhodium, iridium, osmium, ruthenium), rare earth elements (REs: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium), tantalum, titanium, and vanadium to determine their criticality. The committee did not have the time or resources to evaluate all potentially critical minerals; the process used to select and examine these minerals is explained in more detail below. Chapter 5 presents an overview of the federal data, information, and research appropriate for making informed decisions about minerals in general and critical minerals in particular. The main conclusions and recommendations of the study are presented in Chapter 6.

The committee was fortunate in that a complementary study was conducted concurrently by the National Materials Advisory Board of the NRC in which an ad hoc committee assessed the need for a National Defense Stockpile. Therefore, the present committee has included in this report only limited discussion on mineral needs and issues specific to the defense sector and refers the reader to this other NRC report for detailed information.

THE METHODOLOGY: A MINERAL CRITICALITY MATRIX

As the main part of its assessment, the committee developed a methodology—a criticality matrix—to use in assessing a nonfuel mineral's degree of criticality (Figure S.1). The methodology provides a framework for federal agencies, decision makers, the private sector, and any users interested in minerals to make assessments about their own critical minerals and, on that basis, to determine which data, information, and research might be necessary to mitigate potential restrictions in the supply of that mineral for an existing or future use. To be critical, a mineral must be both essential in use (represented on the vertical axis of the matrix) and subject to supply restriction (the horizontal axis of the matrix). Keys to understanding how essential a mineral is in a particular application are its chemical and physical properties. The corollary is that some minerals may be of more concern than others—or have greater *importance in use*—in the sense that few if any substitutes can provide similar functionality at comparable costs. A key to understanding supply restrictions is recognizing that availability—and thus, restriction on availability—depends on the time scale of interest. Fundamentally and over the long term (more than about 10 years), availability is a function of geologic, technical, environmental and social, political, and economic factors. In the short to medium term (a few months to a few years, but less than a decade), availability and reliability of supply can be assessed using a variety of market-specific factors such as worldwide mineral reserve-to-production ratios, world by-product production, U.S. secondary production (through scrap and recycling), import dependence, and the degree to which production is concentrated in a small number of companies or countries. This combination of *importance in use* and *availability or supply risk*—specifically, the potential that an important nonfuel mineral may be subject to supply restrictions—defines a mineral's criticality for any specified time scale.

IMPORTANCE OF MINERALS IN USE

In 2006, the overall value added to the annual gross domestic product by industries that consume processed nonfuel minerals was estimated to be in excess of $2.1 trillion. Mineral industry-related employment, broadly defined, in 2006 was close to 1.5 million jobs. These figures indicate that overall mineral use and associated employment are important to the U.S.

economy. On the other hand, as discussed later, not all mineral use is subject to supply disruption; thus, these figures ought not to be interpreted as indicators of how much of the U.S. economy is at risk should the supply of a specific mineral be restricted.

Understanding the importance of nonfuel minerals in the products from different sectors of the U.S. economy forms the basis for the vertical axis of the committee's criticality matrix, and minerals have varying levels of importance on this axis as a result of the demand for them in a particular end use. "Importance in use" carries with it the concept that some minerals will be more fundamental for specific uses than others, depending on the mineral's chemical and physical properties. Again, by focusing on a mineral's properties, the role of *substitutability* is a key factor in a mineral's importance: a mineral for which substitutes are easily found is going to be slightly less important than one for which substitutes that provide the same properties, at comparable costs, cannot be found in the short term.

Four important industry sectors in the United States—the automotive, aerospace, electronic, and energy sectors—illustrate the use of different minerals in various common applications and highlight the specificity of particular chemical and physical mineral properties for an application. These four sectors were chosen as useful examples for purposes of discussion in this report of mineral criticality, but similar arguments could be made for other important sectors such as health care, construction, utilities, or the transportation infrastructure. All sectors of the economy rely on the services provided by minerals, and the committee was limited by its time and resources to selecting a few industry examples. In determining criticality of specific minerals later in the report, however, the committee took a broader view and included all industry applications, across all industry sectors. In addition to the relationship between mineral properties and mineral substitutability, examination of industrial sectors also lends itself to discussion of the concept that mineral criticality is dynamic: technology advancements, the popularity of given products, the discovery of health or environmental issues related to mineral use, or the rise of regulatory, tariff, or trade issues can all change the level of demand for one or another mineral through time.

An example from the automotive industry illustrates this point. Automobiles manufactured at the start of the twentieth century were composed of about five materials: wood, rubber, steel, glass, and brass. Today, a typical automobile may contain up to 39 different nonfuel minerals in various components, in addition to rubber, plastic, and other organically based materials. Copper, for example, has become the preferred metal for electrical wiring in today's automobiles. About 50 pounds of copper is used in an average automobile today. The new technology of hybrid electric cars requires greater amounts of copper—about 75 pounds in total, by some estimates. PGMs and REs are other families of minerals fundamental to the construction and function of automobile catalytic converters. At present, no viable substitutes exist for these minerals in this application, resulting essentially in a "no-build" situation for catalytic converters should PGM or RE supply be restricted. The report also discusses other examples of mineral applications for the propulsion system and structural frames of airplanes (e.g., titanium), cellular telephones (e.g., tantalum), liquid crystal displays (e.g., indium), computer chips (a broad mineral suite), photovoltaic cells (e.g., silicon, gallium, cadmium, selenium, tellurium, indium), and rechargeable batteries (e.g., lithium, REs, nickel). These examples support the finding that mineral importance changes through time and is largely a function of the properties of minerals and mineral substitutability in a given application.

MINERAL AVAILABILITY OR RISK TO SUPPLY

In evaluating the horizontal axis of the criticality matrix, five dimensions of primary, long-term nonfuel mineral availability were identified: geologic (whether the mineral resource exists), technical (whether we extract and process it), environmental and social (whether we can produce it in environmentally and socially accepted ways), political (whether governments influence availability through their policies and actions), and economic (whether we can produce it at a cost that users are willing and able to pay). With the exception of geologic availability, the same factors apply to the secondary availability of a mineral. Instead of being dependent on its geologic occurrence, the magnitude of the secondary resource depends on past inflows and outflows from the stock of materials available for recycling, including material discarded in landfills.

In the short and medium term, significant restrictions of supply may exist, leading either to physical unavailability of a nonfuel mineral or, more likely, to higher prices. First, *demand may increase significantly and unexpectedly*, and if production already is occurring at close to capacity, either a mineral will become physically unavailable or its price will rise significantly. Second, *relatively thin (or small) markets* may make it difficult to increase production quickly if demand increases significantly. Third, supply may be prone to restriction if *production is concentrated* in a small number of mines, a small number of companies, or a small number of producing countries. Fourth, minerals whose supply consists significantly of *by-product production* may be fragile or risky because the availability of a by-product is determined largely by the availability of the main product (e.g., gallium as a by-product of bauxite mining). Finally, minerals for which there is not significant *recovery of material from old scrap* may be more prone to supply risk than otherwise. Other possible indicators of supply risk, which are commonly cited and possibly useful but only if interpreted with care, are *import dependence*, the *reserve-to-production ratio*, and the ratio of *reserve base-to-production*. These factors can easily be misinterpreted. As outlined earlier in this summary, for example, high measured import reliance does not necessarily imply that supply is at risk. In fact, in several situations, high measured import reliance may be no more risky than domestic supply. The committee found that a balanced interpretation of all of these factors in terms of examination of supply risk is highly dependent on good domestic and global data on nonfuel minerals and mineral markets and comprehensive and reliable analysis of such data.

CRITICAL MINERAL CANDIDATES: APPLICATION OF THE MATRIX

The committee used the 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, PGMs, REs, tantalum, titanium, and vanadium. Because the committee did not have the time or resources to evaluate all potentially critical minerals, these 11 were selected 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 the 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.

Recognizing that restriction in an individual mineral's supply will not have the same macroeconomic impact on the nation as a restriction in the supply of oil, the committee evaluated the criticality of each of these minerals on the basis of whether or not a particular industry sector, or the manufacture of one or more fairly ubiquitous consumer products, would be adversely affected should a restriction on the supply of that mineral occur. The committee acknowledges that some minerals not considered specifically in this report could be soundly argued to be critical to a particular industry, individual, state, community, or federal agency and encourages application of the matrix or similar methodology for these specific needs. Of the 11 minerals examined, PGMs, REs, indium, manganese, and niobium were determined to be critical in the sense that the importance of their applications (in automotive catalytic converters, industrial chemical production, electronics, batteries, liquid crystal displays, or hardeners or strengtheners in steel and iron alloys), the difficulty in finding appropriate mineral substitutes for these applications, and the risk to their supply for any one of a number of reasons were high enough to place these minerals in or near the critical zone on the criticality matrix. Although important applications exist for the other minerals examined by the committee (copper, gallium, lithium, tantalum, titanium, and vanadium), ready substitutes or low risk to their supplies indicate that these minerals are not potentially prone to restriction at present. The committee notes that it did not speculate on the potential for new, or frontier, applications to drive new demand for these or other minerals in the future, underscoring the committee's emphasis on the need for federal collection, analysis, and dissemination of current and consistent data and information on all minerals.

Finally, the committee's application of the matrix methodology—and the particular example of copper—highlights the distinction between minerals that are *essential* to the economy in certain applications but are yet *not critical*, at least at present, because the risk of supply restriction is low. Other minerals likely to fall in this category of essential, but not critical, include bauxite (the mineral raw material for aluminum), iron ore, and construction aggregates.

INFORMATION AND RESEARCH ON MINERALS

Although a wide range of government and nongovernmental, international, and domestic organizations collects and disseminates information and databases relevant for decision making on nonfuel mineral policy issues, the committee found that decision makers in both the public and the private sectors desire continuous, unbiased, and thorough mineral information provided through a federally funded system of information collection and dissemination. Historically, nonfuel mineral data collection in the United States has been a recognized part of national policy since at least World War I, with a foundation in the importance of minerals to the national economy and national security and an emphasis on the importance of good statistical data collection to inform policy decisions. Of the more than 70 federal agencies or programs that receive funding to carry out statistical activities of all types, only 13 are considered "principal" federal statistical agencies. The committee finds it significant that none of the 13 principal statistical agencies collects and publishes annual data on nonfuel minerals and their availability. These principal statistical agencies obtain nearly half of the funding allocated to agencies for statistical data collection, and since their main missions are oriented toward the collection and dissemination of specific types of data, they have a certain degree of autonomy, focus, and ability to maintain the levels of data collection and analysis necessary to support those missions. Agencies that collect data as only one part of their mission may find data collection to be diluted or made subordinate to the overall mission of the agency or department of which they are a part, particularly in situations of constrained resources.

In its examination of federal and nongovernmental sources of information on minerals, the committee concurred with the consensus view of private, academic, and federal professionals that the U.S. Geological Survey (USGS) Minerals Information Team is the most comprehensive, responsible, and responsive source of information on nonfuel minerals both domestically and 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 concomitant reductions in staff and data coverage. Because 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, federal information gathering for nonfuel minerals as presently configured does not have sufficient authority and autonomy to appropriately carry out its data collection, dissemination, and analysis.

In addition to the types of data already appropriately collected by the Minerals Information Team and the resource assessments and research on mineral exploration, production, consumption, and environmental impacts conducted by the USGS Mineral Resources Program under which the Minerals Information Team is administered, the committee is supportive of the incorporation of "critical minerals" as a specific part of analysis and data collection in the context of the complete mineral life cycle. The committee finds domestic and international data collection in the following areas to be useful in this regard: recycling or scrap generation and inventories of old scrap; in-use stocks; reserves and resources; downstream uses; subeconomic resources; and material flows. There currently is no common federal source of information that supplies all of the above data on at least an annual basis for all minerals.

In a number of areas relevant to critical minerals, the committee found a paucity of information. The committee relates these deficiencies to an inappropriately low level of support for research related to resource availability and resource technology. In particular, the following research topics are important if critical minerals are to be reliably identified in the future, if the sources of those minerals (from both virgin and recyclable stocks) are to be better quantified, and if the technology for their extraction and processing is to be substantially enhanced. Areas considered important in this regard include: theoretical geochemical research; extraction and processing and waste disposal technology to improve energy efficiency, to decrease water use, and to enhance material separation; remanufacturing and recycling technology; and the characterization of stocks and flows of materials (especially import and export) as components of products and the losses upon product discard. Aside from nonfuel mineral data collection and analysis, the committee supports federal roles in facilitating and enabling technology transitions and monitoring of markets for new technological applications that employ minerals; the fact that many materials in new applications have come about through government involvement in research and development to achieve higher performance provides validation for this approach.

Finally, the committee found that well-educated resource professionals are essential for fostering the innovation that is necessary to ensure resource availability at acceptable costs with minimal environmental damage. The infrastructure for adequate training of professionals to service the mineral and materials sectors has declined substantially over the past few decades in almost all industrialized countries. The current pipeline of training in the United States does not have enough students to fill the present or anticipated future needs of the country in terms of mineral resource capabilities in the private sector, the federal government, academic institutions, particularly if critical minerals are to be part of the government's mineral data collection, analysis, and dissemination program. While market responses may eventually cover some of the apparent gap between the short-term demand for workers and the supply of new hires, the time lag of market responses, the very large number of anticipated workforce openings, and the need for technology innovation entail larger commitments than the market alone is able to address and suggest the need for government engagement in the matter of professional training.

CONCLUSIONS

Based upon its analysis, the committee draws the following main conclusions:

- **All minerals and mineral products could be or could become critical to some degree, depending on their importance and availability.**
- **From the federal perspective, a critical mineral is one that is both essential in use *and* subject to the risk of supply restriction.**
- **The criticality of a specific mineral can and likely will change as production technologies evolve and new products are developed.**
- **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 mineral supply restriction.**
- **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.** A more nuanced and quantitative version of the matrix could be established and used as part of the federal program for collection, analysis, and dissemination of data on minerals.
- In employing the methodology, **it is important to distinguish among three time or adjustment periods**: **the short term**, **the medium term, and the long term.**
- **In the short and medium terms, significant restrictions of mineral supply may be due to (1) significant increase in demand, (2) thin markets, (3) concentration of production, (4) production**

predominantly as a by-product, (5) lack of available old scrap for recycling or of the infrastructure required for recycling.

- **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. The long-term availability of minerals and mineral products also requires continued investment in mineral education and research.**
- As an indicator of vulnerable supply, **import dependence by itself is not a useful indicator of risk.** Rather, to be vulnerable to supply restriction, some other factor must be present that makes imports vulnerable to disruption—for example, supply is concentrated 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 exported minerals may be redirected toward internal, domestic use.
- Of the 11 minerals or mineral families the committee examined, **those that exhibit the highest degree of criticality at present are indium, manganese, niobium, PGMs, and REs.**
- **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. Federal information gathering for minerals at present does not have sufficient authority and autonomy to appropriately carry out its 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 the status or resources to function 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.**

RECOMMENDATIONS

Recognizing the dynamic nature of mineral supply and demand and of criticality, and in light of the above conclusions, 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 needs to be given to those areas of the mineral life cycle that are underrepresented in current 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 using the committee's matrix 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 organizational 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 minerals 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 research and education on minerals, it is doubtful whether the activities recommended in this report regarding information about minerals will be sufficient for the nation to successfully anticipate and respond to possible short- to long-term restrictions in mineral markets.