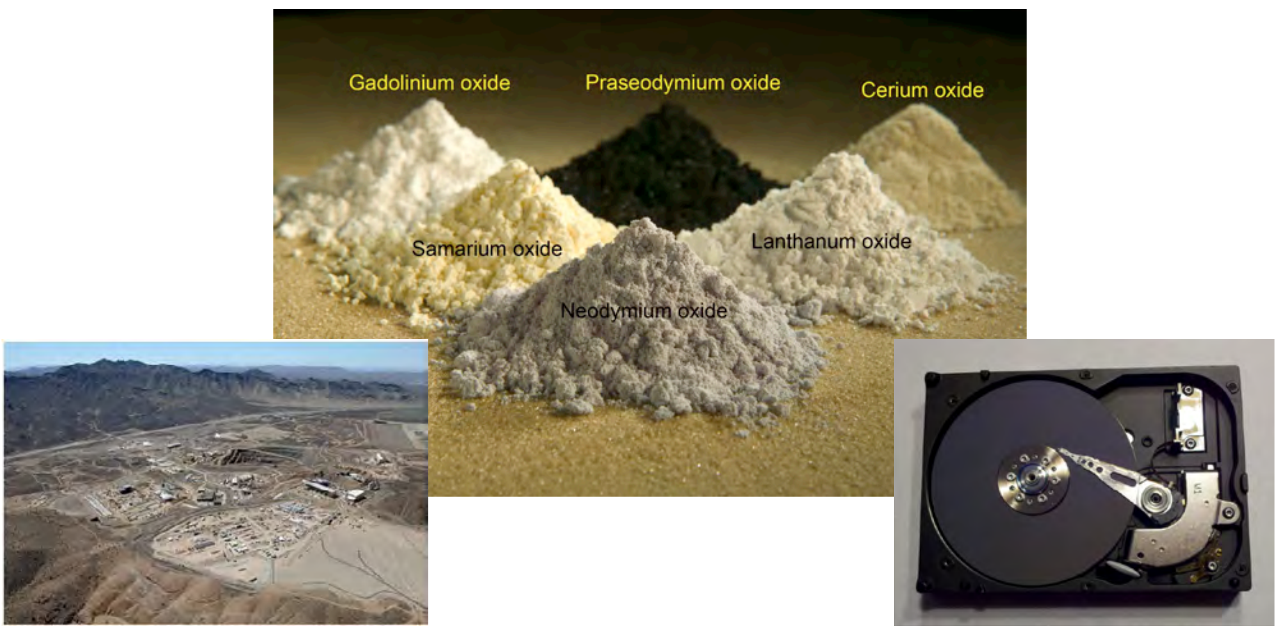
Preliminary Estimates of the Quantities of Rare-Earth Elements Contained in Selected Products and in Imports of Semimanufactured Products to the United States, 2010

By Donald I. Bleiwas and Joseph Gambogi



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Cover. Left: Aerial photograph of Molycorp, Inc.'s Mountain Pass rare-earth oxide mining and processing facilities in Mountain Pass, California. (Photograph courtesy of Molycorp, Inc., used with permission.) Middle: Oxide compounds manufactured from selected rare-earth elements in powdered form. (Photograph courtesy of Peggy Greb, Agricultural Research Center, United States Department of Agriculture.) Right: A hard drive from a personal computer; the spindle motor and a voice coil contain rare-earth magnets.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg); metric ton (t)
ton, long (2,240 lb)	1.016	megagram (Mg); metric ton (t)

SI to Inch/Pound

Multiply	By	To obtain
	Mass	
megagram (Mg); metric ton (t)	1.102	ton, short (2,000 lb)
megagram (Mg); metric ton (t)	0.9842	ton, long (2,240 lb)

Preliminary Estimates of the Quantities of Rare-Earth Elements Contained in Selected Products and in Imports of Semimanufactured Products to the United States, 2010

By Donald I. Bleiwas and Joseph Gambogi

Abstract

Rare-earth elements (REEs) are contained in a wide range of products of economic and strategic importance to the Nation. The REEs may or may not represent a significant component of that product by mass, value, or volume; however, in many cases, the embedded REEs are critical for the device's function. Domestic sources of primary supply and the manufacturing facilities to produce products are inadequate to meet U.S. requirements; therefore, a significant percentage of the supply of REEs and the products that contain them are imported to the United States. In 2011, mines in China produced roughly 97 percent of the world's supply of REEs, and the country's production of these elements will likely dominate global supply until at least 2020. Preliminary estimates of the types and amount of rare-earth elements, reported as oxides, in semimanufactured form and the amounts used for electric vehicle batteries, catalytic converters, computers, and other applications were developed to provide a perspective on the Nation's use of these elements. The amount of rare-earth metals recovered from recycling, remanufacturing, and reuse is negligible when the tonnage of products that contain REEs deposited in landfills and retained in storage is considered. Under favorable market conditions, the recovery of REEs from obsolete products could potentially displace a portion of the supply from primary sources.

Introduction

Because of the United States' reliance on nondomestic suppliers of rare-earth elements (REEs), identification of the types and amounts of REEs imported both as impure and refined metals and oxides and intermediate (semimanufactured) products, as well as those contained (embedded) in the components of a wide range of products presently in use, is of economic and strategic importance to the Nation. These types of information help in determining the significance of disruptions in the supply of these materials, as well as the amounts of REEs that are potentially available for recycling.

REEs embedded in products may or may not represent a significant component of that product by weight, value, or volume; however, in many cases, the embedded REEs are critical for the device's function. For example, the neodymium-iron-boron magnets used in the spindle motors and voice coils of personal computers are considered embedded materials, and although the magnets make up only a small portion of the computer, they are essential to its function.

This report provides the results of initial research undertaken by the U.S. Geological Survey (USGS) to assess the amount of REEs that flow through the U.S. economy annually. This research has thus far focused on assessing the quantity of REEs contained in selected products in use in the United States and in selected imports of intermediate products in 2010. Some chemical and mineralogical information on REEs and on current sources of production is also included.

Chemical Classification of Rare-Earth Elements

The International Union of Pure and Applied Chemistry defines the REEs as the set of 15 chemical elements in the periodic table with atomic numbers 57 through 71 (the lanthanides), plus scandium and yttrium (Connelly and others, 2005). The lanthanides include, in order of atomic number, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Several rare-earth metal oxides in powdered form are shown in figure 1.

Figure 1. The oxides of rare-earth metals gadolinium (Gd), praseodymium (Pr), cerium (Ce), samarium (Sm), lanthanum (La), and neodymium (Nd) in powdered form. Photograph courtesy of Peggy Greb, Agricultural Research Center, U.S. Department of Agriculture.

REEs are often classified as either light rare-earth elements (LREEs) or heavy rare-earth elements (HREEs). The classification is based in part on the LREEs having unpaired electrons in the 4f electron shell and HREEs having paired electrons in the 4f electron shell. The LREEs include the elements from atomic number 57 (lanthanum) through atomic number 64 (gadolinium); the HREEs include the elements from atomic number 65 (terbium) through atomic number 71 (lutetium) and also yttrium (atomic number 39).

Mineralogical Occurrence of Rare-Earth Elements

The principal ores from which REEs are extracted are characterized by the minerals bastnäsite, loparite, monazite, lateritic ion-adsorption clays, and xenotime. Bastnäsite is the leading ore mineral source of REEs in the world; it is enriched with cerium, lanthanum, neodymium, praseodymium, and other REE (U.S. Bureau of Mines and U.S. Geological Survey, 1980). Historically, bastnäsite has been a source primarily of LREEs. Bastnäsite is produced in China and the United States. Loparite, which is an oxide that contains niobium, REEs, sodium, and titanium, occurs with certain alkaline rocks of magmatic origin. One mine in Russia produces loparite containing 30 to 36 percent REEs. Monazite is a phosphate mineral that contains REEs and the radioactive element thorium. Although monazite has been and could be produced as a byproduct of many heavy-mineral operations, limited demand for thorium, and in some cases, environmental concerns associated with the radioactive nature of the mineral, has led all domestic and most foreign producers to stop recovering monazite. Monazite continues to be produced in Brazil and India. Xenotime, a phosphate mineral that is rich in yttrium and HREEs, has been produced from cassiterite deposits in Malaysia and is a potential byproduct from the production of certain heavy-mineral placer deposits. Lateritic deposits in Jiangxi Province in southern China contain lateritic ion-adsorption clays that have rare-earth ions adsorbed into their mineral structure. These deposits make up the world's principal supply source of yttrium and the other HREEs (Gambogi and Cordier, 2012). Table 1 shows the percentage distribution of REEs (by type of ore) of major producing sites in China and the United States.

Table 1. Percentage distribution of rare-earth elements by type of ore at major production sites in the United States and China.

[Data are percentage of total rare-earth elements in ore and are rounded to no more than three significant digits; may not add to totals shown. Rare-earth elements are listed in ascending order of atomic number]

Rare-earth element	Bastnäsite		Monazite
	Mountain Pass, Calif., United States[1]	Bayan Obo, Inner Mongolia, China[2]	Nangang, Guangdong, China[3]
Yttrium	0.10	trace	2.40
Lanthanum	33.20	23.00	23.00
Cerium	49.10	50.00	42.70
Praseodymium	4.34	6.20	4.10
Neodymium	12.00	18.50	17.00
Samarium	0.80	0.80	3.00
Europium	0.10	0.20	0.10
Gadolinium	0.20	0.70	2.00
Terbium	trace	0.10	0.70
Dysprosium	trace	0.10	0.80
Holmium	trace	trace	0.12
Erbium	trace	trace	0.30
Thulium	trace	trace	trace
Ytterbium	trace	trace	2.40
Lutetium	trace	trace	0.14
Total	100	100	100

Rare-earth element	Xenotime	Rare-earth laterite	
	Southeast Guangdong, China[4]	Xunwu, Jiangxi Province, China[5]	Longnan, Jiangxi Province, China[5]
Yttrium	59.30	8.00	65.00
Lanthanum	1.20	43.40	1.82
Cerium	3.00	2.40	0.40
Praseodymium	0.60	9.00	0.70
Neodymium	3.50	31.70	3.00
Samarium	2.20	3.90	2.80
Europium	0.20	0.50	0.10

Table 1. Percentage distribution of rare-earth elements by type of ore at major production sites in the United States and China.—Continued

[Data are percentage of total rare-earth elements in ore and are rounded to no more than three significant digits; may not add to totals shown. Rare-earth elements are listed in ascending order of atomic number]

	Xenotime	Rare-earth laterite	
	Southeast Guangdong, China[4]	Xunwu, Jiangxi Province, China[5]	Longnan, Jiangxi Province, China[5]
Gadolinium	5.00	3.00	6.90
Terbium	1.20	trace	1.30
Dysprosium	9.10	trace	6.70
Holmium	2.60	trace	1.60
Erbium	5.60	trace	4.90
Thulium	1.30	trace	0.70
Ytterbium	6.00	0.30	2.50
Lutetium	1.80	0.10	0.40
Total	100	100	100

[1]Johnson and Sisneros, 1981.

[2]Zang and others, 1982.

[3]Xi, Zhang, 1986.

[4]Nakamura, 1988.

[5]Government of Jiangxi Province, 1985.

How Rare-Earth Elements Are Used

REEs were first isolated by researchers in the late 1700s. It was not until the 1930s that the unique characteristics of REEs found commercial application when cerium oxide was employed as a component of compounds used to polish glass. The chemical reaction of the compound with glass forms cerium silicate, which fills microscopic scratches in the glass; this chemical change, along with cerium's physical hardness, makes it an excellent polishing agent. The next significant commercial application was introduced in the 1960s when europium and yttrium were incorporated as components of phosphors to produce red in color television images (Gschneidner and Capellen, 1987; Gupta and Krishnamurthy, 2005). By the beginning of the 21st century, REEs (individually and in combination with other REEs) were components in more than 200 products across a wide range of applications, including batteries, catalysts, ceramics, electronics, glass, lasers, medicine, phosphors, polishes, and metallic alloys (including permanent magnets) (Gupta and Krishnamurthy, 2005). The elements are used in such common high-tech consumer products as cellular telephones, computer hard drives, electric and hybrid vehicles, and flat-screen monitors and televisions. They are also used in a significant array of defense applications, including in actuators on the fins of guided missiles and other munitions, such as smart bombs; electronic displays; fiber optics; guidance systems for drone aircraft; lasers for various applications; optics, such as lenses and night vision systems; and radar and sonar systems (Rare Earth Industry and Technology Association, 2009; Robinson, 2011). Table 2 lists some common applications of REEs.

Table 2. Examples of common applications of rare-earth elements.

Application	Chemical element[1]																
	Sc	Y	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Alloys and metallurgical uses	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Batteries			X	X	X	X	X				X						
Catalysts		X	X	X	X	X		X		X							X
Ceramics	X	X	X	X	X	X		X	X	X		X	X	X	X		X
Electronics		X	X	X	X	X					X	X		X			
Fertilizers			X	X		X											
Glass	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Lamps	X	X	X	X	X			X	X		X	X	X	X	X		
Lasers	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Magnets				X	X	X		X	X	X	X	X	X				
Medical and pharmaceutical uses			X	X		X		X	X	X			X	X			X
Neutron absorption		X		X				X	X	X		X	X	X			
Phosphors	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X

[1]The symbols used for chemical elements in this table include the following (in order of atomic number): Sc, scandium; Y, yttrium, La, lanthanum; Ce, cerium; Pr, praseodymium; Nd, neodymium; Pm, promethium; Sm, samarium; Eu, europium; Gd, gadolinium; Tb, terbium; Dy, dysprosium; Ho, holmium; Er, erbium; Tm, thulium; Yb, ytterbium; and Lu, lutetium.

Heavy rare-earth elements (HREEs) are less abundant relative to the light rare-earth elements (LREEs). Among the most important HREEs used in advanced technologies are dysprosium, europium, neodymium, terbium, and yttrium. HREEs (especially dysprosium, europium, neodymium, terbium, and yttrium) are typically less common in rare-earth mineral deposits than are LREEs (table 1). The market price per unit of rare-earth-oxide equivalent for HREEs is considerably higher than for LREEs given the relatively strong demand for them coupled with their relative scarcity. Because of their importance for advanced technologies, an increase in the demand for HREEs is likely unless substitutions are discovered or advances are made to existing technologies so the products do not require—or at least require less—of the rare-earth metals.

Exploration Activity and Vulnerability of Supply

Exploration activity at present emphasizes the search for deposits that are relatively high in HREEs (rather than LREEs) because of the anticipated proportionately greater increase in demand and higher value of HREEs than LREEs. It is likely, however, that China will remain the only significant primary source of most HREEs, such as dysprosium, for the next several years (Gimurtu, 2012). The development of REE deposits is based on factors that include the elemental distribution of the REEs and the grade and tonnage, the mineral processing requirements, the geographic location, and the environmental remediation requirements. Numerous exploration and development projects are underway that may not only increase world production of REEs but also introduce new sources of supply. By 2018, significant new or expanded mine production may be underway in Australia, Canada, Greenland, South Africa, Sweden, and the United States.

To address questions of supply and demand for REEs, in 2011, the 111th U.S. Congress mandated that the U.S. Secretary of Defense conduct an assessment of REE supply-chain issues and develop a plan to address the country's vulnerability to supply shortages. The U.S. Department of Defense was required to assess which REEs meet the following criteria: (a) the rare-earth material is critical to the production, sustainment, or operation of significant U.S. military equipment; and (b) the rare-earth material is subject to interruption of supply based on actions or events outside the control of the Government of the United States. In March 2012, the DOD identified seven REEs (dysprosium, erbium, europium, gadolinium, neodymium, praseodymium, and yttrium) that were critical to the production, sustainment, or operation of significant U.S. military equipment and were subject to the interruption of supply. New U.S. production of the seven REEs was expected to satisfy consumption for defense needs, with the exception of yttrium. Additional assessments of the REE supply chain were ongoing.

In 2012, the United States joined with Japan and the European Union to bring a World Trade Organization (WTO) joint-dispute-resolution case against China. The case was brought because of China's restrictive policies on trade of certain rare-earth and other minerals (Bailey Grasso, 2012). The WTO's review of the case is ongoing.

Current Sources of Production

The United States relies primarily on nondomestic sources of production for its supply of REEs. In 2011, mines in China produced roughly 97 percent of the world's supply of REEs. Much of the output from China, especially the more valuable HREEs, was used within China to produce value-added products, many of which were exported. Although modest changes to global supply patterns could take place in the next few years, a significant portion of the global supply chain of rare-earth ores and concentrates and of refined, intermediate, and final products that contain rare-earth metals is likely to be firmly anchored to China through at least 2020. The world supply of intermediate materials, components, and finished products that contain rare-earth metals also originates in Asia, especially Japan. These include refined metals and such products as consumer goods, electronic components, and permanent magnets that are made from materials supplied mainly by China. Some of these intermediate products are then exported back to China, assembled into finished products, and exported to global consumers.

With respect to domestic production, about 3,000 metric tons (t) of rare-earth-oxide equivalents was produced from stockpiled concentrate at Molycorp Inc.'s Mountain Pass Mine in California in 2011 (fig. 2; Elmquist, 2011; Sullivan, 2012). The mine originally opened as a relatively small operation in 1952, but it dominated world REE production from the 1960s through the 1990s (Olson and others, 1954). Mining of ore was halted in 2002 for economic and environmental reasons, although processing of previously mined ore continued (Molycorp, Inc., 2012b). In 2012, the Mountain Pass operation began once again to mine ore, and Molycorp expected to produce 19,050 t of rare-earth oxide equivalents by the end of the third quarter of 2012 (Molycorp, Inc., 2012a). As of the end of 2012, the Mountain Pass Mine was the only domestic source of primary REEs. Except for a small amount of material that is recycled, the balance of REEs and intermediate compounds containing REEs in the United States and much of the components and products in which REEs are incorporated have been imported. In 2012, Molycorp reported that it had entered into several agreements to supply cerium, lanthanum, neodymium, and other rare-earth-based products to domestic and foreign companies from the Mountain Pass operation and from recently acquired subsidiaries in Arizona and Estonia (Mining.com, 2011).

Figure 2. Aerial photograph of Molycorp, Inc.'s Mountain Pass rare-earth oxide mining and processing facilities in Mountain Pass, California. Photograph courtesy of Molycorp, Inc., used with permission.

Preliminary Estimates of Quantities of Rare-Earth Elements in Manufactured and Imported Products in the United States

Determination of the amount (tonnage) of REEs entering the U.S. economy or in service at a particular time period can be approximated by collecting data on (a) how the metal is used (its applications), (b) the amount of the metal that is used in specific products, and (c) the number of units produced and (or) sold. Such data are necessarily rough estimates because the amounts of material used in similar products can differ; also, companies often consider this type of information to be confidential and the data are therefore unavailable. For example, data pertaining to the composition and amounts of domestically produced cerium-based glass-polishing compounds, which is a major use for cerium, were not able to be estimated for this report because of the confidential nature of the data. Once the types, proportions, and weight of rare-earth metals and other elements contained in components of "typical" products are known, the data can then be multiplied by the estimated number of units that entered the economy to come up with the rough estimate of the tonnage entering the economy.

Table 3 lists the estimated tonnage of REEs, expressed in terms of oxides (the industry standard), contained in selected products that entered the U.S. economy in 2010. It was compiled using the approach discussed above. Most of the estimates for contained rare-earth metals in table 3 were developed from published information that is publicly available and from data provided by sources in Government agencies, industry, and universities. The estimates were developed for 2010 primarily from import-export data from UBM Global Trade's Port Import/Export Reporting Service (PIERS) and from data collected, maintained, and analyzed by the USGS, other Federal agencies, and private companies. In addition, numerous disc drives and mobile phones were dismantled and their magnets removed and weighed to obtain data on embedded REEs. In some cases, a manufacturer's labeling of a component was used to determine its rare-earth content. Consumption data were derived from an assortment of statistics that included the number of units imported, domestic sales, and unit production. The estimates in table 3 will likely be revised as new information is received and (or) becomes available.

Approximately 12,000 t of rare-earth oxides was contained in the selected products shown in table 3, of which nearly 65 percent was lanthanum oxide used in electric and hybrid vehicles and fluid catalytic cracking catalysts for petroleum. Neodymium oxide and cerium oxide each composed 14 percent of the total. Neodymium is an important component of magnets in electronic devices and in catalysts used in petroleum refining. About 80 percent of the cerium oxide was used in automotive catalytic converters.

Table 3 indicates that, in 2010, roughly 15,000 t of rare-earth oxides was contained in imported impure metals and oxides, refined metals and oxides, and intermediate products. Some of these materials were reexported in their original form and as intermediate and finished products. About 53 percent of the contained REEs was lanthanum oxide and 24 percent was cerium oxide. Most of the lanthanum oxide was for the domestic manufacture of automotive catalytic converters, batteries, and catalysts for petroleum cracking (the largest use, by weight, of REEs in the United States), and phosphors for light bulbs. Cerium was imported primarily as cerium oxide and was used mostly in the production of automotive catalytic converters, phosphors, and for glass polish. Oxides of cerium, lanthanum, europium, terbium, and yttrium were contained in imports of fluorescent bulbs (the great majority of fluorescent bulbs are not produced in the United States). The intermediate products included magnets, primarily of the neodymium-iron-boron type, that have a broad range of applications, including computers with hard drives (fig. 3), phosphors for lighting, and compounds used in producing nickel-metal hydride batteries. Assembled, or “finished,” products are not included in the data in table 3.

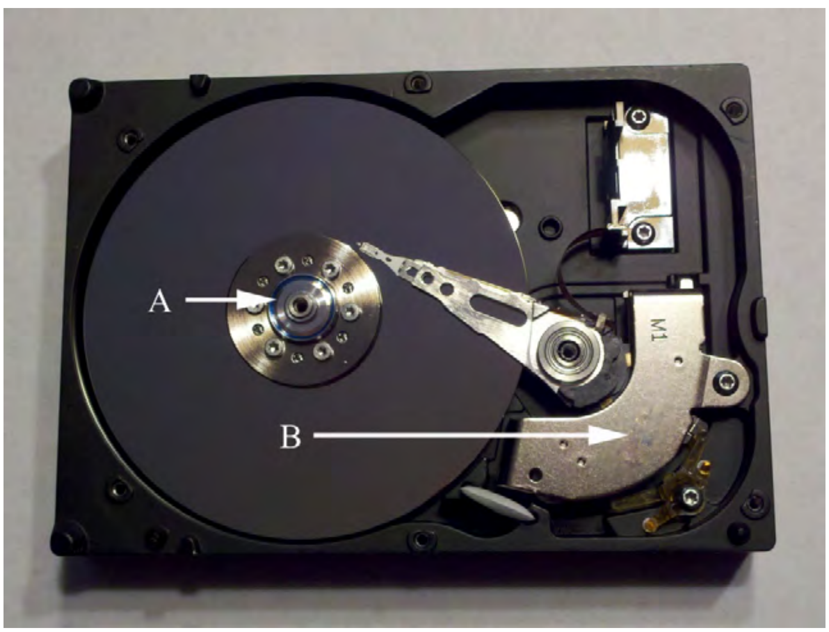

Figure 3. Photograph of a hard drive from a personal computer showing (A) a spindle motor and (B) a voice coil that contain rare-earth magnets.

Table 3. Estimated weight (in metric tons) of rare-earth oxides contained in selected manufactured products that entered service in the United States in 2010 and in material containing rare-earth metals that was imported into the United States in 2010.

[Estimates are rounded to two significant figures. t, metric tons; dashes (--), no data; Do., ditto.; LED, light-emitting diode; OEM, original equipment manufacturer. Rare-earth oxides: CeO_2, cerium oxide; Dy_2O_3, dysprosium oxide; Er_2O_3, erbium oxide; Eu_2O_3, europium oxide; Gd_2O_3, gadolinium oxide; La_2O_3, lanthanum oxide; Lu_2O_3, lutetium oxide; Nd_2O_3, neodymium oxide; Pr_6O_{11}, praseodymium oxide; Sm_2O_3, samarium oxide; Tb_4O_7, terbium oxide; Y_2O_3, yttrium oxide]

General application	Product	CeO_2	Dy_2O_3	Er_2O_3	Eu_2O_3	Gd_2O_3	La_2O_3	Lu_2O_3	Nd_2O_3	Pr_6O_{11}	Sm_2O_3	Tb_4O_7	Y_2O_3	Undetermined rare-earth oxides
Mass of compound in manufactured products that entered service in 2010, in metric tons														
Alloys	Zinc-based coatings for light-gage steel supports[1]	5.6	--	--	--	--	2.4	--	--	--	--	--	--	--
Batteries	Electric and hybrid vehicles		--	--	--	--	4,000	--	--	--	--	--	--	--
Catalysts	Automotive catalytic converters	1,400	--	--	--	--		--	--	--	--	--	--	--
Do.	Fluid catalytic cracking (FCC) catalysts for petroleum refining	210	--	--	--	--	3,400	--	640	--	--	--	--	--
Magnets	Automotive (general applications)	--	4.5	--	--	--	--	--	76	--	--	--	--	--
Do.	Cell phone and other mobile devices	--	--	--	--	--	--	--	86	4.2	--	--	--	--
Do.	Electric and hybrid vehicle motors	--	40	--	--	--	--	--	300	--	--	--	--	--
Do.	Electronic power steering in vehicles	--	--	--	--	--	--	--	26	1.7	--	--	--	--
Do.	External disc drives for servers	--	--	--	--	--	--	--	61	4.2	--	--	--	--
Do.	Game consoles	--	--	--	--	--	--	--	64	4.5	--	--	--	--
Do.	OEM speakers in vehicles	--	--	--	--	--	--	--	7	5	--	--	--	--
Do.	Personal computers and laptops	--	--	--	--	--	--	--	440	30	--	--	--	--

Table 3. Estimated weight (in metric tons) of rare-earth oxides contained in selected manufactured products that entered service in the United States in 2010 and in material containing rare-earth metals that was imported into the United States in 2010.—Continued

[Estimates are rounded to two significant figures. t, metric tons; dashes (--), no data; Do., ditto.; LED, light-emitting diode; OEM, original equipment manufacturer. Rare-earth oxides: CeO_2, cerium oxide; Dy_2O_3, dysprosium oxide; Er_2O_3, erbium oxide; Eu_2O_3, europium oxide; Gd_2O_3, gadolinium oxide; La_2O_3, lanthanum oxide; Lu_2O_3, lutetium oxide; Nd_2O_3, neodymium oxide; Pr_6O_{11}, praseodymium oxide; Sm_2O_3, samarium oxide; Tb_4O_7, terbium oxide; Y_2O_3, yttrium oxide]

General application	Product	CeO_2	Dy_2O_3	Er_2O_3	Eu_2O_3	Gd_2O_3	La_2O_3	Lu_2O_3	Nd_2O_3	Pr_6O_{11}	Sm_2O_3	Tb_4O_7	Y_2O_3	Undetermined rare-earth oxides
Mass of compound in manufactured products that entered service in 2010, in metric tons—Continued														
Phosphors	Fluorescent bulbs[2]	130	--	--	50	--	200	--	--	--	--	56	740	--
Phosphors and diodes	LED televisions[3]	0.0057	--	--	0.0049	--	--	--	--	--	--	--	0.11	--
Solutions	Imaging contrast dye	--	--	--	--	23 to 70	--	--	--	--	--	--	--	--
TOTAL		1,700	45		50	23 to 70	7,600		1,700	50		56	740	--
Mass of compound in materials imported in 2010, in metric tons														
Catalysts, electronics, fuel additives, glass, imaging contrast dyes, magnets, nuclear fuel rods, phosphors, polishing powders, and others	Imported refined metal and oxides, impure, and intermediate products[4, 5]	3,600	25	33	25	80	7,900	27	590	94	8.8	4.2	670	1,500[6]

[1]Includes only GALFAN®, which contains approximately 0.1 percent rare-earth oxide in a hot-dip coat that makes up about 2 percent of the total weight of the steel.

[2]Includes phosphors used in tube-type and compact fluorescent lights.

[3]Estimates are based on the number of LED televisions sold in the United States in 2010 and assumes a 42-inch screen.

[4]Some material may be exported in various forms. Estimate does not include finished products, such as contrast dye.

[5]Based on United Business Media Global Trade Port Import/Export Reporting Service (PIERS) data for 2010.

[6]Based on limited data. The material was assumed to be bastnäsite and was estimated to contain 740 t CeO_2, 510 t La_2O_3, 170 t Nd_2O_3; 62 t Pr_6O_{11}, and a small amount of other rare-earth oxides.

The column in table 3 titled "undetermined rare-earth oxides" includes imported tonnages of rare-earth shipments that did not include detailed descriptive data. Most of the reported tonnage was labeled as "rare earth," "rare-earth metal and misch metal," "rare-earth oxide," or "rare-earth carbonate." The material was presumed to be mostly bastnäsite concentrates, based on the limited information available from the PIERS listings and other sources. The country of origin was usually listed as China. The amount and type of rare-earth oxides contained in this column in table 3 were assumed to have a rare-earth-oxide content similar to the bastnäsite ore that occurs at the Mountain Pass deposit in California, which is similar to China's Bayan Obo deposit. The Mountain Pass bastnäsite reportedly has a rare-earth oxide distribution of 49.59 percent CeO_2, 33.79 percent La_2O_3, 11.16 percent Nd_2O_3, 4.12 percent Pr_6O_{11}, 0.85 percent Sm_2O_3, 0.21 percent Gd_2O_3, 0.13 percent Y_2O_3, 0.11 percent Eu_2O_3, 0.03 percent Dy_2O_3, 0.02 percent Tb_4O_7, and 0.01 percent Er_2O_3 (Castor, 2008).

Based on reported data through August 2011, the estimated 2011 distribution of REEs contained in intermediate materials imported and produced from stockpiles of concentrate at Mountain Pass by end use was as follows, in decreasing order of amount used: catalysts, 47 percent; metallurgical applications and alloys, 24 percent; alloys, glass polishing, and ceramics, 10 percent; permanent magnets, 9 percent; ceramics, 5 percent; and rare-earth phosphors used in computer monitors, lighting, radar, and televisions, and x-ray-intensifying film, 5 percent. REEs embedded in finished products are not included (Gambogi, 2013).

The estimates of REEs contained in imported refined metal and oxides, impure metals and oxides, and intermediate products produced from U.S. sourced material shown in table 3 are not necessarily additive with the data reported for selected products. For example, the estimate of 80 t of gadolinium oxide contained in imported refined metals and oxides, impure metals and oxides, and intermediate products does not include finished products, such as contrast dyes [a common and heavily used material injected into patients that undergo magnetic resonance imaging (MRI) scans]. Most of the estimated gadolinium oxide contained in contrast dyes shown in table 3 is imported from several countries in ready-to-use solutions. Only a relatively small amount of the gadolinium contained in such solutions is manufactured by companies in the United States. The data suggest that a significant amount of the imported gadolinium is used in other domestically produced products, such as capacitors and thermal barrier coatings on turbine engines and the turbine blades of aircraft engines. The amount of neodymium oxide imported also appears to be significantly less than the amount of neodymium oxide contained in just the few selected products shown in table 3 and indicates the heavy import reliance of the United States on embedded materials in consumer products and other items that contain REEs.

Additional Research Ongoing and Planned

REEs contained in imports of unfinished products are used for the domestic production of catalysts, electroceramics, diesel fuel additives, glass, and phosphors for various applications, all of which remain to be researched. Also, a detailed estimate of the amount of cerium used for glass polishing annually in the United States has not yet been developed.

Rare-earth permanent magnets, primarily of neodymium-iron-boron type, are used in many of the motors that drive cordless tools, elevators, heating and air conditioning systems, home appliances, and wind-driven residential and commercial generators and represent a significant amount of the total domestic use of this type of REE. An estimate of the rare-earth materials contained in these products, most of which are imported, is ongoing.

The use of REEs as alloying agents in steel is another major application. Niobium and REEs are added to some types of steel to make it lighter, stronger, and more resistant to heat and corrosion. These specialty steels are used in such applications as aerospace, bridges, buildings, car bodies, oil and gas pipelines, rail tracks, ship hulls, and wind turbines (Gupta and Krishnamurthy, 2005; Quantum Rare Earth Developments Corp., 2012). The rare-earth metal content varies depending on the application, but usually ranges from 0.1 to 0.35 percent. Based on the limited information collected thus far, the annual U.S. consumption of the steels could exceed 10 million metric tons (Tretheway and Jackman, 1981). The total amount of rare-earth metals contained in domestic production and imports of this type of steel has not been estimated and will be a complex task because of the limited amount of data available that pertains to the great number of intermediate and finished products and variations in rare-earth metal content.

Although estimating the amount of REEs contained in products that enter the U.S. economy annually is a significant challenge, another challenge is understanding the use and ultimate fate of these products as they flow through the economy to the end of their serviceable life because they may contain recoverable or potentially recoverable material. Because REEs are chemically very similar and used in relatively minute quantities, REEs are difficult to separate from finished products. The amount of rare-earth metals recovered from recycling, remanufacturing, and reuse (RRR) is negligible when the tonnage of products that contain REEs deposited in landfills and retained in storage is considered. Under favorable market conditions, a domestic supply of rare-earth metals created by RRR could offset a portion of the supply from primary sources among which the HREE would have significant strategic value to the United States.

Summary and Preliminary Conclusions

The assemblage and distribution of REEs contained in ore deposits varies. The uses of the elements are diverse and have some important strategic applications for which there are few substitutes. The heavier elements of the group are more highly valued because they are rarer and have very specific industrial applications. Although the development of additional sources of ore and intermediate products is emerging in other countries, such as Australia and the United States, the production of rare-earth ores in China and the intermediate and finished products manufactured from them will likely continue to dominate global supply until at least 2020.

Noting the annual imports of REEs contained as refined metals and oxides, impure metals and oxides, and intermediate products and comparing them with preliminary estimates of U.S. consumption of rare-earth metals contained in a sampling of products and their country of origin demonstrates that the United States is more heavily dependent on imports of REEs than is indicated by imports of processed rare-earth materials alone. The export of products from the United States that contain REEs is also a factor to be considered in analyzing the United States dependence on REEs and the United States' vulnerability to disruptions in supply. Even with the development of domestic sources of raw, intermediate, and refined REEs and the development of domestic manufacturing of permanent magnets, the United States is likely to continue to rely on significant quantities of the elements embedded in imported goods because, for a number of reasons, there is insufficient domestic manufacturing capacity for many fully assembled products, such as personal computers, to meet domestic demand. Domestic mining production and processing of the ore, however, could serve at least in part as an alternate source for domestic manufacturers and as a source of supply to companies in other countries that manufacture products that contain REEs that the United States imports, such as personal computers. A domestic supply or stockpile would also guarantee a source of REEs for strategic military applications, such as lasers, guidance systems, night vision apparatus, and actuators.

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