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Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues

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National Risk Management Research Laboratory
Office of Research and Development
Cincinnati, OH

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments, and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Rare earth elements (REEs) are a group of 15 chemical elements in the periodic table, specifically the lanthanides. Two other elements, scandium and yttrium, have a similar physiochemistry to the lanthanides, are commonly found in the same mineral assemblages, and are often referred to as REEs. Although relatively abundant in the earth's crust, they rarely occur in concentrated forms, making them economically challenging to obtain. These elements comprise critical components of many of our modern-day technological devices and everyday electronics. REE demand in the United States is projected to increase given global demand for green and sustainable products in energy, military, and manufacturing uses. China has

been providing 95% of REEs worldwide but the United States is increasing its interest in exploring and mining REEs.

Mining in the natural environment comprises the majority of acquisition of REEs and, like most mining operations, results in a large quantity (greater than 90 percent) of excess and un-used materials. At present, there is no formal EPA or national strategy existing for managing resource development and mitigation of impacts during the acquisition, use, and disposal of REEs. The purpose of this document has been to compile current information to develop a strategy for managing REE resources and reducing potential environmental impacts. Though the vast majority of information in this report is current, as noted in this report, mining and extraction of REEs is dynamic. For example, we recognize global market prices for REE's have declined since mid-2011 when this report was completed. Therefore, some details regarding who is producing what and where may have changed between the time when: (1) data collection as part of the literature search for this report was completed in July 2011, and (2) the report's contract was completed in September 2011, and (3) its subsequent publication in 2012.

This document provides a description of the many environmental facets of the rare earth mining and disposal issues, and explains the need for a national strategy for the continued supply of required REEs in future technological development nationally and internationally, and for the reuse of these materials versus disposal in landfills.

Cynthia Sonich-Mullin, Director
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Abstract

Rare earth elements (REEs) are a group of 15 chemical elements in the periodic table, specifically the lanthanides. Two other elements, scandium and yttrium, have a similar physiochemistry to the lanthanides, are commonly found in the same mineral assemblages, and are often referred to as REEs. REEs have not been mined in the United States for about 20 years, and prior to that time, the amount of mining was minimal compared to coal and hard rock mining. The increased use of REEs in magnets, modern electronics and in a variety of commercial products has led to a shortage of REEs for production purposes. Currently, REEs are being disposed in large quantities rather than being recovered and reused.

The purpose of this report is to serve as a technical information resource to policy makers and other stakeholders who are concerned with the potential environmental and health effects and impacts that can be identified across the REE supply chain. RTI conducted a search of the technical literature and other Internet sources related to each segment of the supply chain, including recent initiatives of U.S. government agencies that document issues associated with REE production, processing, manufacturing, end uses, recycling, and health/ecological effects. Information contained in this report also draws upon past domestic and international experience, as appropriate.

Compared to coal and other hardrock mining, the scope of REE mining has always been very small, both in the U.S. and globally. No major REE mining operations have been conducted in the U.S. since 1995. Mining and processing activities have the potential to create a number of environmental risks to human health and the environment. The severity of these risks is highly variable between mine and mine plant operations. The contaminants of concern will vary depending on the REE-mineral ore, the toxicity of the contaminants from the waste rock, ore stockpiles, and process waste streams. The mobility of contaminants will be controlled by the characteristics of the geologic, hydrologic, and hydrogeologic environments where the mine is located, along with the characteristics of the mining process and waste handling methods.

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Throughout the development of the document, monthly teleconference calls took place among members of the REE work group and was comprised of the following individuals who gratefully gave their time and expertise voluntarily. Dr. Michael McKittrick of ORD National Center for Environmental Research (NCER), Dr. Robert Seal of the U.S. Geological Survey, Dr. David Drake of EPA Region 7, and Kathleen Graham of ORD/OSP in EPA Region 8 played a key role in developing this issue over less than a year. Additionally, special thanks go out to Jim Sims and Scott Honan of MolyCorp, Inc. for providing input on their current REE mining and resource recovery processes. We would also like to acknowledge the reviews and constructive comments provided by Karen Pollard and William Schoenborn of the Office of Solid Waste and Emergency Response, Dr. Anne Riederer of the ORD Assistant Administrator's office, Diana Bless (ORD), and Holly Elwood of the Office of Pesticide Programs and Toxic Substances. Finally, we would also like to thank our current (and former) immediate management, Albert Venosa and Randy Parker in EPA ORD/NRMRL, Maggie LaVay of EPA ORD/OSP, Nigel Fields, formerly of EPA ORD/OSP (now with DOI/NPS), and Gene Gunn and Dr. David Drake in EPA Region 7, for their support of our work.

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List of Acronyms

AMD	acidic or alkaline mine drainage
ARD	acid rock drainage
BLM	Bureau of Land Management
CLERCA	Comprehensive Environmental Response, Compensation and Liability Act
CO_2	carbon dioxide
CR3	Center for Resource Recovery and Recycling
CREI	Colorado Rare Earths Incorporated
CSM	Conceptual Site Model
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EIS	environmental impact statement
ES	environmental study
EU	European Union
HCl	hydrochloric acid
ISL	in situ leach
HREE	heavy rare earth element
LCD	liquid crystal display
LREE	light rare earth element
MIW	mining-influenced water
NaOH	sodium hydroxide
NEDO	New Energy and Industrial Technology Development Organization
NEPA	National Environmental Policy Act
NIMS	National Institute for Material Science
NMD	neutral mine drainage
NORM	naturally occurring radioactive material
ORD	Office of Research and Development
PCB	polychlorinated biphenyl
PFD	neutral mine drainage
RCRA	Resource Conservation and Recovery Act
REACT	Rare Earth Alternatives in Critical Technologies
REE	rare earth element
REM	rare earth metal

REO	rare earth oxide
RESTART Act	Rare Earths Supply-Chain Technology and Resources Transformation Act of 2010
RO	reverse osmosis
RTI	RTI International
TDS	total dissolved solids
TENORM	technologically enhanced, naturally occurring radioactive material
UN	United Nations
UNEP	United Nations Environment Programme
USGS	U.S. Geological Survey
VOC	volatile organic compounds

1. Introduction

1.1 Background

Rare earth elements (REEs) are a group of 15 chemical elements in the periodic table, specifically the lanthanides. Two other elements, scandium and yttrium, have a similar physiochemistry to the lanthanides, are commonly found in the same mineral assemblages, and are often referred to as REEs. Although relatively abundant in the earth's crust, REEs rarely occur in concentrated forms, making them economically challenging to obtain. These elements constitute critical components of many important technologies and products, such as hybrid vehicles, wind turbines, and cell phones. Given this global demand for green and sustainable products in energy, military, and manufacturing industries, REE demand in the United States and throughout the world is projected to increase.

In recent years, China has been providing 95 to 97 percent of REEs worldwide. Because China has demonstrated its ability to control and limit REE exports, it is crucial that the United States expand its ability to obtain REE resources. Mining in the natural environment is the primary means of REE acquisition; however, it results in a large quantity (greater than 90 percent) of excess and unused materials and other environmental impacts. If the United States is to ensure a continuous supply of REEs, responsible mining practices will need to be developed and enhanced. Additionally, effective recycling, recovery, and reuse of spent consumer and industrial products may reduce the need to develop new mineral resource areas.

To obtain up-to-date information on the environmental aspects and potential impacts of REE mining, recovery, recycling, and reuse, the U.S. Environmental Protection Agency (EPA) Office of Research and Development's (ORD's) Engineering Technical Support Center contracted with RTI International (RTI) to conduct a literature review and to develop this report.

The purpose of this report is to serve as a technical information resource to policy makers and other stakeholders who are concerned with the potential environmental and health effects and impacts that can be identified across the REE supply chain. This document is not a life-cycle assessment or a risk assessment. However, it does, to the extent possible based on anticipated, proposed, or past practices, attempt to identify environmental compartments (i.e., aquatic environment, terrestrial environment, and air) that may be at risk and the corresponding environmental loads (e.g., raw material consumption, air emissions, water discharges, wastes), when that information is available in the literature or an association can be made with anticipated, current, and past practices.

RTI conducted a search of the technical literature and other Internet sources related to each segment of the supply chain, including recent initiatives of U.S. government agencies (i.e., U.S. Geological Survey [USGS], U.S. Department of Energy [DOE], and the EPA) that document issues associated with REE production, processing, manufacturing, end uses, recycling, and health/ecological effects. Information contained in this report also draws upon past domestic and international experience (United Nations Environment Programme [UNEP]), as appropriate.

1.2 Report Organization

This report is organized into eight sections and appendices, as follows:

- ***Section 1*** provides the overall background for the project.
- ***Section 2*** provides general background information on REEs, including information on their uses, their reserves in the United States, and their current supplies and demand worldwide.
- ***Section 3*** provides information on REE mining operations and potential environmental impacts.

- ***Section 4*** focuses on beneficiation and processing, along with associated environmental impacts, and includes information related to the Molycorp Minerals mine in Mountain Pass, California, which is scheduled to resume full-scale production in 2012.
- ***Section 5*** summarizes the steps associated with REE recycling and provides information on the status of commercial recycling processes. This section also includes information on potential alternatives to REEs and a summary of new policies and programs that will impact future recycling.
- ***Section 6*** summarizes information from the literature on health and environmental issues associated with REEs.
- ***Section 7*** presents a summary of the report information, a list of key findings, and recommended next steps.
- ***Section 8*** provides a reference list.
- ***Appendix A*** describes selected chemical properties of REEs; ***Appendix B*** provides a table with locations of REE-producing mines and REE-containing mineral deposits in the United States; and ***Appendix C*** presents process flow diagrams of REE extraction and processing operations.

This report is envisioned as a starting point for the ORD to investigate potential environmental and health issues concerning the production, processing, recycling, recovery, and life cycle of REEs. This report is an overview intended to set the framework for these issues and should not be viewed as a comprehensive document on REEs and the mining of those materials.

2. Introduction to Rare Earth Elements

For the purposes of this report, the series of 15 lanthanide metals, plus scandium and yttrium, have been designated as REEs; however, it should be noted that other elements also are sometimes referred to as REEs. Rare earth oxides (REOs), and rare earth metals (REMs). While these elements are widely dispersed and generally common in nature, minable concentrations of REEs are less common than for most other metal ores. Rare earths have become important in modern commercial and industrial processing and products. Metallurgical processing, alloying, and electronics applications (e.g., cell phones, computer components, electric motors, specialty glass and lenses) represent the most significant uses of REEs. In addition, due to the dependence on several of these elements for military applications, REEs are considered a national strategic resource. Analysis of the future supply and demand for each of the REEs indicates that, by 2014, global demand could exceed 200,000 tons per year, which would exceed current production by over 75,000 tons per year. It is reported that if the new mines under development are able to meet their projected production levels, world-wide demand for REEs will be met from these new sources.

The International Union of Pure and Applied Chemistry, an organization devoted to maintaining international consistency for chemical nomenclature, has identified the15 transition metals from the periodic table of the elements with atomic numbers 57 (lanthanum) through 71 (lutetium) as lanthanides or lanthanoids. These 15 elements share common physiochemical properties and are listed below:

- Lanthanum ($_{57}$La)
- Cerium ($_{58}$Ce)
- Praseodymium ($_{59}$Pr)
- Neodymium ($_{60}$Nd)
- Promethium ($_{61}$Pm)
- Samarium ($_{62}$Sm)
- Europium ($_{63}$Eu)
- Gadolinium ($_{64}$Gd)
- Terbium ($_{65}$Tb)
- Dysprosium ($_{66}$Dy)
- Holmium ($_{67}$Ho)
- Erbium ($_{68}$Er)
- Thulium ($_{69}$Tm)
- Ytterbium ($_{70}$Yb)
- Lutetium ($_{71}$Lu).

Due to their similar physiochemistry, these lanthanides often occur together as elemental constituents of their host minerals. Two other metals commonly found in association with lanthanides in the same mineral assemblages are the following:

- Scandium ($_{21}$Sc)
- Yttrium ($_{39}$Y).

These two metals also have physiochemical characteristics that are very similar to the lanthanides.

2.1 Abundance of REEs in Earth's Crust

Together, the lanthanides, yttrium, and scandium are commonly referred to as REEs or REMs, although this is a misnomer since most of the REEs are common mineral constituents as compared with other metal elements. The term "rare" is a carryover from metallurgical chemists from around the 1940s (Gupta and Krishnamurthy, 2004). The metallurgical processes needed to isolate the individual metal species are complex, and early technology prevented commodity-level production. As a result, lanthanide metals or metal oxides (i.e., REOs) were difficult to obtain and thus are considered rare. The abundance of REEs in the earth's crust relative to other common metals is presented in **Table 2-1**; these abundances from Wedephol (1995) are only one of several interpretations, but those presented here are generally representative. As shown in the comparison, the content of lanthanides relative to other REEs in rock-forming minerals is not rare at all.

Table 2-1. Abundance of Elements in the Earth's Crust (Wedepohl, 1995)

Elements	Crustal Abundance (parts per million)
Nickel ($_{28}$Ni)	90
Zinc ($_{30}$Zn)	79
Copper ($_{29}$Cu)	68
Cerium ($_{58}$Ce)[a]	**60.0**
Lanthanum ($_{57}$La)	**30.0**
Cobalt ($_{27}$Co)	30
Neodymium ($_{60}$Nd)	**27.0**
Yttrium ($_{39}$Y)	**24.0**
Scandium ($_{21}$Sc)	**16.0**
Lead ($_{82}$Pb)	10
Praseodymium ($_{59}$Pr)	**6.7**
Thorium ($_{90}$Th)	6
Samarium ($_{62}$Sm)	**5.3**
Gadolinium ($_{64}$Gd)	**4.0**
Dysprosium ($_{66}$Dy)	**3.8**
Tin ($_{50}$Tn)	2.2
Erbium ($_{68}$Er)	**2.1**
Ytterbium ($_{70}$Yb)	**2.0**
Europium ($_{63}$Eu)	**1.3**
Holmium ($_{67}$Ho)	**0.8**
Terbium ($_{65}$Tb)	**0.7**
Lutetium ($_{71}$Lu)	**0.4**
Thulium ($_{69}$Tm)	**0.3**
Silver ($_{47}$Ag)	0.08
Gold ($_{79}$Au)	0.0031
Promethium ($_{61}$Pm)	10^{-18}

[a] Lanthanides (lanthanoids), scandium, and yttrium are presented in boldface type.

Following a common pattern within the periodic table, the lanthanides with even atomic numbers are more common in nature. Additionally, early on, geochemists observed a pattern in the occurrence and crustal abundance of some lanthanides. Lanthanides with lower atomic numbers were noted to be more common ionic constituents in REE mineral ores and, in general, occurred in greater abundance than the lanthanide elements with higher atomic numbers.

These observed trends in crustal abundance among the geochemical models suggest a divide between light and heavy lanthanide-enriched minerals. Although variation exists, one example of an REE classification is presented in **Figure 2-1** and shows the division between light REEs (LREEs) and heavy REEs (HREEs) (Schuler et al., 2011). Some investigators classify gadolinium and dysprosium as medium-weight lanthanides due to their physiochemical properties. Additional information on REE chemistry and other classifications is provided in ***Appendix A***.

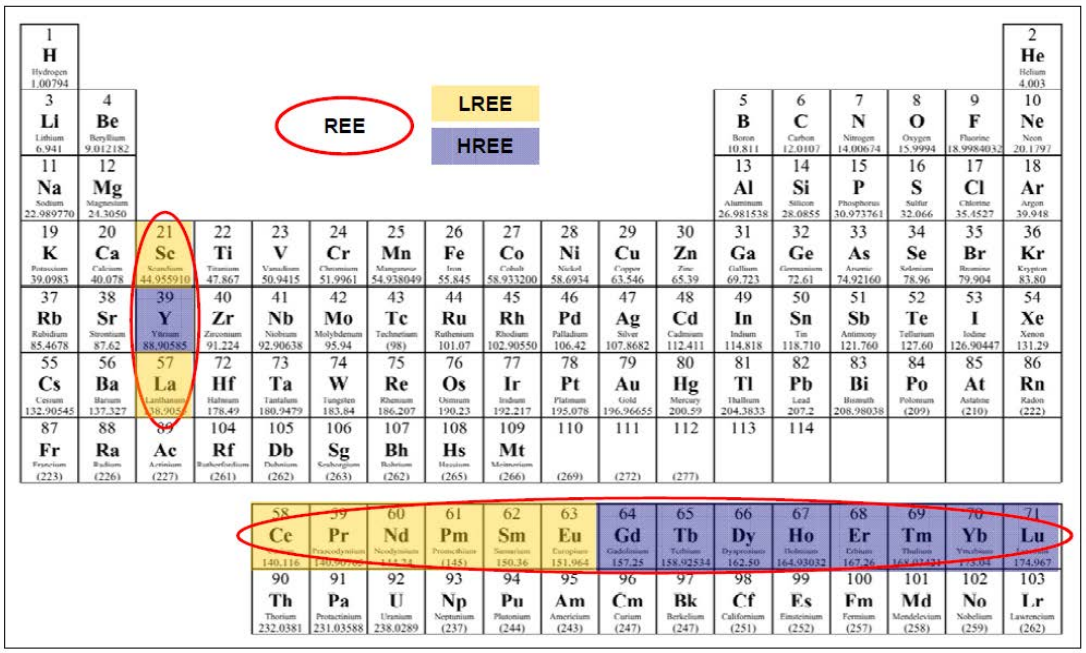

Figure 2-1. Periodic table of the elements showing the division between LREEs and HREEs (Schuler et al., 2011).

The elemental forms of REEs that are extracted from mineral ores, as oxides (i.e., REOs), are iron-gray to silvery lustrous metals that are typically soft, malleable, ductile, and usually reactive, especially at elevated temperatures or when finely divided. The REEs' unique properties are used in a wide variety of applications. For example, magnets made with REEs are much more powerful, weigh less, and can be made smaller than conventional magnets. Some REEs also have high electrical conductivity, can withstand extreme heat, and give off intense white light when heated.

In aquatic systems, REEs typically occur in the trivalent state. However, cerium can be present as Ce^{4+} and europium can occur in both the divalent and trivalent states. The chemical behaviors of all REEs are very similar, but smooth variations can be attributed to their atomic number and ionic radii, which are inversely correlated. These attributes make REEs well suited to the study of processes such as complexation, sorption, precipitation, and the formation of colloids (Merten and Büchel, 2004).

2.2 Geologic Environments of REEs

REEs do not occur as native elemental metals in nature, only as part of the host mineral's chemistry. For this reason, the recovery of REMs must be accomplished through a complex processing method (described in ***Section 4***) to chemically break down the minerals containing the REEs.

Despite more than 200 known REE-bearing minerals, only three are considered to be the principal REE mineral ores most feasible for the extraction of REMs: bastnasite, xenotime, and monazite (Gupta and Krishnamurthy, 2004), as described below:

- Bastnasite, the most abundant among the three REE mineral ores, is a carbonate mineral found mainly enriched in LREEs (e.g., cerium, lanthanum, and yttrium). Bastnasite is found in vein deposits, contact metamorphic zones, and pegmatites. It forms in carbonate-silicate rocks occurring with and related to alkaline intrusions (e.g., Mountain Pass mine).
- The two phosphate minerals, xenotime and monazite, can occur together, but crystallize in different temperature and pressure regimes from a similar igneous environment. While these

minerals can contain any of the REEs (i.e., HREEs or LREEs), enrichment of specific REEs is variable and a function of the temperature and pressure regime in which they formed. Monazite commonly occurs in placer deposits; xenotime can occur along with monazite, but generally occurs as a more minor constituent of these types of deposits. Deposits of phosphate rare earth ores provide the opportunity to produce co-products of phosphates and REEs. Thorium and uranium may also be taken advantage of and produced as a co-product, or may represent a significant management challenge. A further description of these two minerals follows:

  - Monazite is generally enriched with the LREEs cerium, lanthanum, and neodymium, but can also contain HREEs, particularly yttrium (Ni et al., 1995). The predominance of LREEs is due to the lower crystallization temperature and pressures of this mineral; however, it typically contains more HREEs than bastnasite ore deposits. It occurs in acidic igneous rocks (primarily pegmatites), metamorphic rocks, and some vein deposits. Monazite is resistant to weathering and occurs in many placer deposits as the host rocks are eroded. Thorium may also be associated with monazite in various amounts.
  - Xenotime crystallizes under higher temperatures and pressures than those of monazite; therefore, its crystalline structure more readily accommodates a higher ratio of HREEs (terbium through lutetium, and yttrium) than is commonly found in monazite. It is primarily a yttrium phosphate mineral and occurs as a minor constituent of granitic and gneissic rocks. Although not always present in significant quantities, uranium and thorium can also occur as constituents of xenotime.

- There are two other important REE-containing minerals in the United States (Long et al., 2010) including:
  - Euxenite which contains yttrium, erbium, and cerium. It is found mostly in placer deposits in Idaho, and occurs as a tantaloniobates (e.g., minerals where Ta and Nb form the compound) of titanium, rare earths, thorium, and uranium.
  - Allanite is an epidote mineral and contains cerium, lanthanum, and yttrium. It occurs in igneous, metamorphic, and hydrothermal environments and is disseminated in pegmatite or occurs in vein deposits.

These five minerals are considered to represent the principal occurrences and the potentially more significant REE reserves in the United States (USGS, 2010). However, many other minerals containing REEs do occur, and deposits of these minerals could be found in the United States and prove to be viable for mining. It is also not uncommon for REEs to be produced as a coproduct or byproduct of other mineral production. A list of minerals that commonly contain REEs is presented in the USGS report by Long et al. (2010).

The principal future domestic supply of REEs is one carbonatite formation in Mountain Pass, California. Other common and potentially viable deposit types containing almost exclusively the two phosphate REE-bearing minerals (monazite and xenotime) are most common as placer ores that originated from the erosion of pegmatite granites and related gneisses. The general occurrences of rock types that host REE-containing mineral ores in the United States are shown in **Figure 2-2**.

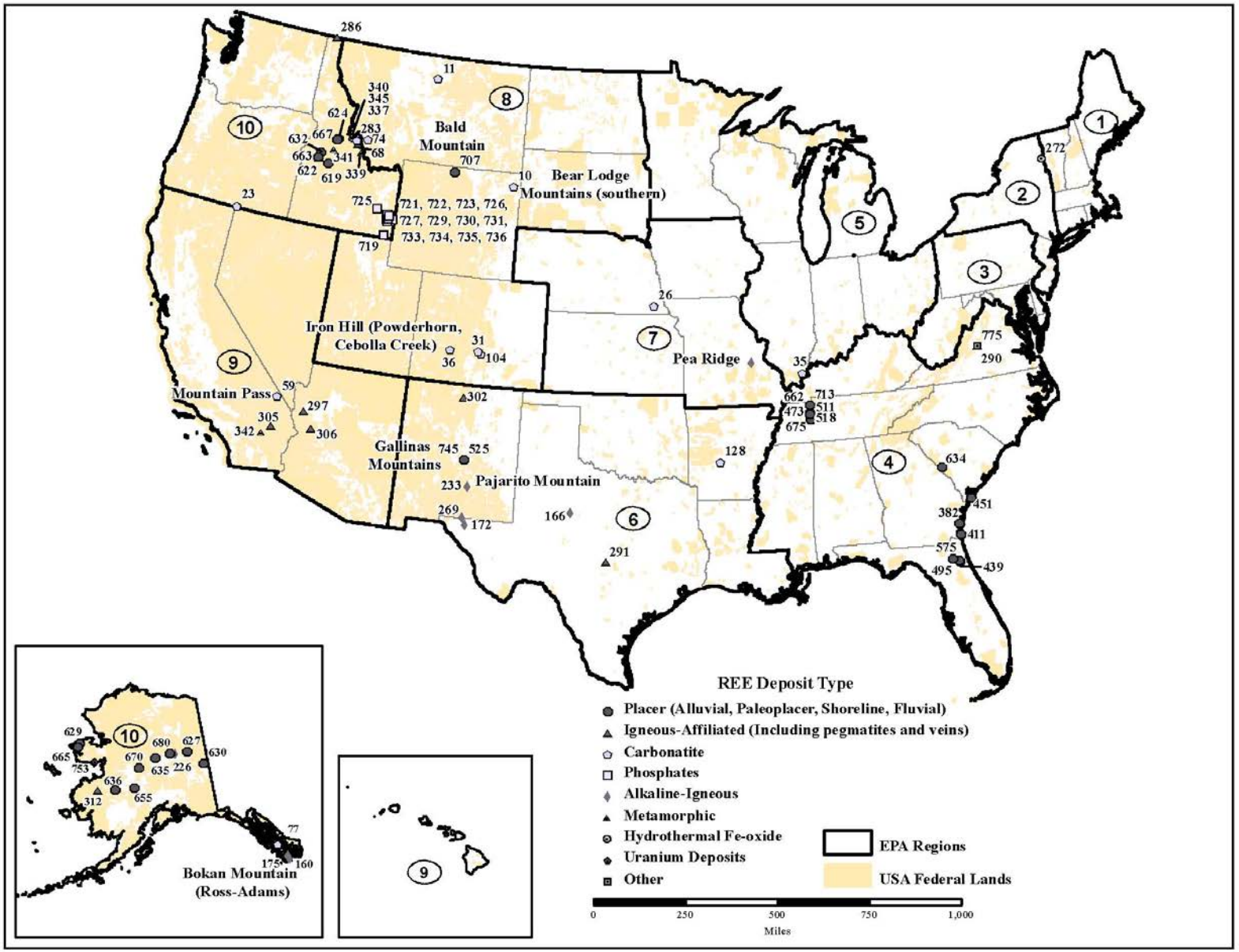

Figure 2-2. Map showing occurrences of REEs, by rock type (adapted from multiple sources, see *Appendix B*).

2.3 Applications of REEs

The REEs and their key applications are identified in **Table 2-2**. Also included in the table are the (1) key categories of uses by the U.S. Department of Defense (DoD) and (2) DOE's classification of the elements determined to be critical or near critical due to projected supply risks and their importance to clean-energy technologies. **Figure 2-3** graphically presents additional information on the specific types and quantities of REEs that were reported as being in use in various products in 2007. **Table 2-3**, taken from USGS data, provides a breakdown by industrial application on the uses of REEs in the United States in 2008.

Table 2-2. Rare Earth Elements, Their Applications, and Potential Supply Issues for Clean-Energy Technologies

Element	Applications
Scandium	Metal alloys for the aerospace industry.
Yttrium	Ceramics; metal alloys; lasers; fuel efficiency; microwave communication for satellite industries; color televisions; computer monitors; temperature sensors. Used by DoD in targeting and weapon systems and communication devices. Defined by DOE as critical in the short- and mid-term based on projected supply risks and importance to clean-energy technologies.
Lanthanum	Batteries; catalysts for petroleum refining; electric car batteries; high-tech digital cameras; video cameras; laptop batteries; X-ray films; lasers. Used by DoD in communication devices. Defined by DOE as near critical in the short-term based on projected supply risks and importance to clean-energy technologies.
Cerium	Catalysts; polishing; metal alloys; lens polishes (for glass, television faceplates, mirrors, optical glass, silicon microprocessors, and disk drives). Defined by DOE as near critical in the short-term based on projected supply risks and importance to clean-energy technologies.
Praseodymium	Improved magnet corrosion resistance; pigment; searchlights; airport signal lenses; photographic filters. Used by DoD in guidance and control systems and electric motors.
Neodymium	High-power magnets for laptops, lasers, fluid-fracking catalysts. Used by DoD in guidance and control systems, electric motors, and communication devices. Defined by DOE as critical in the short- and mid-term based on projected supply risks and importance to clean-energy technologies.
Promethium	Beta radiation source, fluid-fracking catalysts.
Samarium	High-temperature magnets, reactor control rods. Used by DoD in guidance and control systems and electric motors.
Europium	Liquid crystal displays (LCDs), fluorescent lighting, glass additives. Used by DoD in targeting and weapon systems and communication devices. Defined by DOE as critical in the short- and mid-term based on projected supply risks and importance to clean-energy technologies.
Gadolinium	Magnetic resonance imaging contrast agent, glass additives.
Terbium	Phosphors for lighting and display. Used by DoD in guidance and control systems, targeting and weapon systems, and electric motors. Defined by DOE as critical in the short- and mid-term based on projected supply risks and importance to clean-energy technologies.
Dysprosium	High-power magnets, lasers. Used by DoD in guidance and control systems and electric motors. Defined by DOE as critical in the short- and mid-term based on projected supply risks and importance to clean-energy technologies.
Holmium	Highest power magnets known.
Erbium	Lasers, glass colorant.
Thulium	High-power magnets.
Ytterbium	Fiber-optic technology, solar panels, alloys (stainless steel), lasers, radiation source for portable X-ray units.
Lutetium	X-ray phosphors.

Source: U.S. DOE, 2011.

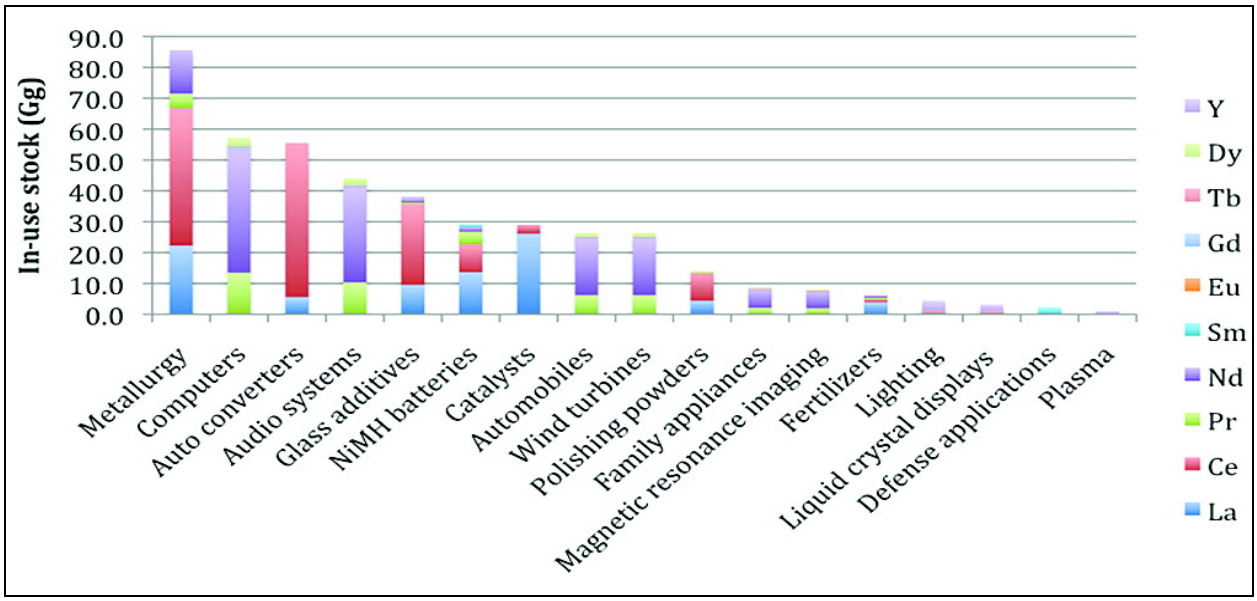

Figure 2-3. In-use stocks of selected REEs by specific application or industry (in gigagrams) (Du and Graedel, 2011).

Table 2-3. Distribution of REEs by End Use in 2008 (U.S. DOI/USGS, 2010)

End Use	Percentage
Metallurgical applications and alloys	29%
Electronics	18%
Chemical catalysts	14%
Rare earth phosphors for computer monitors, lighting, radar, televisions, and X-ray-intensifying film	12%
Automotive catalytic converters	9%
Glass polishing and ceramics	6%
Permanent magnets	5%
Petroleum refining catalysts	4%
Other	3%

2.4 REE Global Economic Supply and Demand

From the 1960s until the 1980s, the United States was the world leader in REO production. In fact, in 1984, the Mountain Pass Mine in California supplied 100 percent of U.S. demand and 33 percent of the world's demand for rare earths. In the late 1970s, China started increasing production of REEs, and as illustrated in **Figure 2-4**, rapidly became the world's dominant producer. Active mining operations at Mountain Pass Mine were suspended in 2002. Since 2007, separation of REE from stockpiles at the site has continued. As REE production in the U.S. has declined, China has become the world's leading producer of REEs and is currently responsible for more than 95 percent of global production.

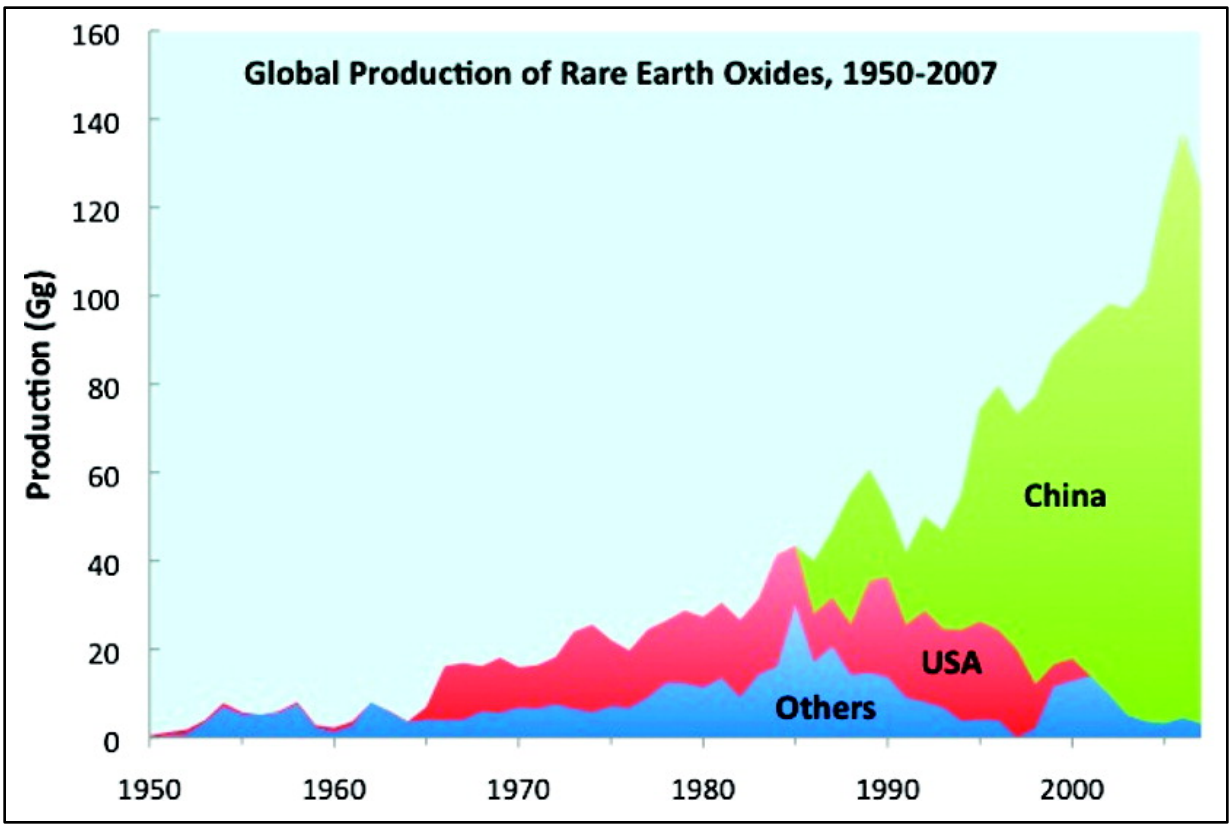

Figure 2-4. Global production of rare earth oxides (Du and Graedel, 2011).

Annual global production of REEs totaled about 124,000 tons in 2008, according to a recent report by the U.S. Congressional Research Service (Humphries, 2010). According to this same report, analysis of the future supply and demand for each of the REEs indicates that, by 2014, global demand could exceed 200,000 tons per year, which would exceed current production by over 75,000 tons per year. Additional analysis by others indicates the high likelihood of shortages of neodymium, dysprosium, terbium, and praseodymium and the potential for shortages of lanthanum, yttrium, and, europium by 2014 (Schuler et al., 2011). This information, combined with the data shown in Figure 2-3, indicates that the uses most likely to be impacted by future shortages are magnets for use in computers, audio systems, wind turbines, and automobiles; motors/generators; batteries; metallurgy; and catalysts. The critical nature of these uses is driving the push for increased mining, expanded recycling and research into alternatives, and changes in U.S. and international policy.

In 2008, the United States consumed 7,410 metric tons of REEs (U.S. DOI/USGS, 2010). Currently, this demand is met mainly through imports from China, industry inventories, and stockpiles. However, as early as 2012, U.S. production may be resumed at the Mountain Pass Mine, which is projecting production of 18,000 tons in 2012 and up to 40,000 tons per year in following years. The status and critical issues facing this mine, as well as other potential U.S. mines, are presented in **Table 2-4**. It is reported that if the new mines under development are able to meet their projected production levels, world-wide demand for REEs will be met from these new sources (Long, 2011).

Table 2-4. Current Activities at Selected, Potential U.S. REE Mines

Factor	Mountain Pass (California), RCF, Goldman Sachs, and Traxys	Bear Lodge (Wyoming), Rare Element Resources Ltd.	Pea Ridge (Missouri), Upland Wings/Wings Enterprises and Glencore International	Round Top Mountain Project (Texas), Texas Rare Earth Company
Status	Recommissioned separation plant. Feasibility study of recommencing mining and processing under way.	Resource engineering study under way. Process development commenced.	Commercial and technical studies ongoing. Property ownership has changed to Pea Ridge Resources, Inc..	Exploration—potential open pit mine. 82,000 feet of drill core available for evaluation. Preparing for aeromagnetic survey and additional drilling.
Resources	20 Mt @ 9.2% rare earth oxides (REO); 1.8 Mt REO contained (a proven reserve).	9 Mt @ 4.1% REO 0.4 Mt REO (inferred).	4 Mt iron ore; $3 billion of REE; small HREE deposit, but potentially higher concentrations than in any deposit worldwide.	67% of REOs are HREEs.
Potential Production	Target: 18,000 tons per year REO; start-up in 2012.	Unknown.	Output of REE from tailing unknown; underground mine production unknown.	Information not available.
Critical Issues	▪ New owners. ▪ Completing Definitive Feasibility Study (DFS). ▪ Restarting an "old" plant.	▪ Define "ore reserve." ▪ Develop process. ▪ Complete DFS. ▪ Approvals. ▪ Customer support.	▪ Define "ore reserve." ▪ Develop process. ▪ Complete DFS. ▪ Approvals. ▪ Customer support.	▪ Information not available.

Sources: http://phx.corporate-ir.net/phoenix.zhtml?c=236277&p=irol-news&nyo=0; http://www.rareelementresources.com/s/Home.asp; http://www.wingsironore.com/; http://texasrareearth.com/; http://pearidgeresources.com/

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3. Life-Cycle Stages of Rare Earth Mineral Mines

The increasing importance of REMs for the manufacture of modern devices upon which society has become reliant, along with uncertain supplies (see ***Section 2***), is encouraging exploration and development of new mining sites. While REMs are an important resource needed to sustain our modern technologies, the waste footprint and environmental impact from REM mining operations is expected to be as significant as current mining practices for metals and minerals. The requirements, regulations, and financial obligations and assurances for a new mine are usually complex and take years of planning. The economic feasibility of discovered deposits must be proved, and environmental effects to the local communities and habitat also must be evaluated to determine feasibility. The process of exploration, development, and construction typically required before mining can begin may exceed 10 years. Except for a few locations, known rare earth deposits in the United States are generally considered small to medium reserves. This section presents a discussion of the typical process steps used in developing a new rare earth deposit and the associated mining wastes that typically would result. It is not expected that the mining stages of a rare earth mine would be different than other hardrock or metal mining operations. Except for the radioactivity of uranium and thorium, the potential REM waste emissions would be generally comparable to a typical hardrock mine.

Mining operations produce a variety of solid materials that have the potential to cause environmental contamination and require long-term remedial actions and operation and maintenance. The largest mines may generate more than a billion tons of solid wastes that may cover areas exceeding a thousand acres, and smaller operations still must handle and dispose of quantities of materials that can affect large areas (U.S. EPA, 2003). Most deposits of REE ores in the United States would be expected to require mining operations that likely would produce far less quantities of solid wastes than the largest operating mines. An example of an existing REE mine in the United States that would be considered a large mining operation, is the Molycorp Minerals rare earth mine in Mountain Pass, California (see sidebar). It would be expected that rare earth mineral mining operations developed in the United States would be similar to other large hardrock and placer mines that recover minerals containing primary metals (e.g., gold, silver, copper, zinc, lead). As examples, the mass of selected types of individual REE-containing ore deposits occurring in the United States is estimated by the USGS to be the following:

- 0.2 million tons (approximate average) for thorium-rare earth vein deposits (Armbrustmacher et al., 1995)
- 3.5 to 450 million tons for low titanium iron oxide deposits containing REE, with a median quantity of 40 million tons (Foose, 1995)
- 6.6 to 331 million tons for minable carbonatite ore deposits (Modreski et al., 1995).

These rough quantity estimates are based on known deposits, as characterized in geochemical deposit models prepared by the USGS; other deposit models may also exist other than those found and reviewed and that provide additional estimates. Averages for the

The Scale of an Existing REE Mine in the United States

The largest rare earth minerals mine in the United States is Molycorp Mineral's Mountain Pass rare earth mine and site, which occupies 2,222 acres of land in San Bernardino County, California. The mine started operation in 1952, operating as an open pit lanthanide mining, beneficiation, and processing facility. The period of greatest ore production was from 1965 to 1995. Mining activities ceased in 2002, but minor milling activity continued to process stockpiled ore; and full-scale ore production may resume in 2012. When mining activities ceased, the open pit was 1,500-feet wide by 400-feet deep. Overburden materials were held on site, and numerous process water, tailings, and product storage ponds were also operated.

Remaining REE reserves (relative to a 5 percent cutoff grade) at the Mountain Pass mine are estimated to exceed 20 million tons. The average REE content in the bastnasite mineral ore is approximately 9 percent. The remaining gangue minerals (calcite, barite, and dolomite) in the carbonatite igneous rock body make up approximately 91 percent of the ore-containing rock. The expected overburden produced is estimated to be 104 million tons, which will be stored at two existing storage piles. These storage piles will together cover approximately 315 acres within 30 years of the proposed period of operation through 2042 and represent approximately a 120 percent change over current stockpiles accumulated between 1950 and 2002.

California Regional Water Quality Control Board, Lahontan Region (2010)

mass of overburden and waste rock that might be removed from aboveground mining operations are not provided in these models. The amount of overburden and waste rock depends on many factors, including the type of deposit, the geometry of the ore body, and the mining method. In general, overburden includes the sediments or rock materials below the soil horizon that must be removed from above and possibly around a subsurface deposit and that does not contain concentrations of the commodity mined. Overburden does *not* include the mass of waste rock removed from around the economically viable ore. Waste rock may represent a subeconomic ore material, removed from around or within specific regions of the ore body, that does not contain appreciable quantities or concentrations of the mined commodity relative to the target ore. Waste rock is removed to reach the more economically viable regions of the ore-containing rock. Subeconomic ore specifically refers to conventionally mined ore with a grade that is not rich enough to meet the current market condition for viable production. Mines classify their subeconomic to uneconomic material based on potential for future processing, given appropriate market conditions and environmental risks. Active mining can encounter all variations in the concentration of the commodity in the rock or sediments being extracted, depending upon the complexity of the ore body. The waste rock material is generally managed separately from the overburden piles since the waste rock can contain higher concentrations of metals that, if released, may have environmental consequences. Clearly, the efforts and resources required for management of overburden, waste rock, and ore materials alone are generally significant. Management of the soil and rock material removed from the mine is necessary since these materials may contain concentrations of metals, acid-producing sulfides, and radioactive elements. Freshly exposed rock surfaces enhance the effects of weathering and can allow release of metals as environmental contaminants, which may represent a potential human and ecological health risk to site workers, nearby residents, nearby recreational users, and aquatic and terrestrial species and habitat. However, REE ores generally contain few acid-producing sulfide minerals, so the risk of producing acids to leach metals and producing mine drainage (AMD) is considered low. Because REE deposits are associated with igneous rocks, the greatest AMD risk would probably come from these igneous bodies intruding sediments or other rocks containing sulfide minerals.

3.1 Active REE Mining

As of this writing, ongoing active mining operations for extraction of REE ores are not widespread in the United States. Aboveground mining of REEs last occurred in the United States in 2002 (Long et al., 2010) at the Molycorp Minerals rare earth mine in Mountain Pass, California (**Figure 3-1**). Currently, the Molycorp mine is preparing to resume ore production, but initial start-up plans are for operations to begin with processing of stockpiled ore (Jim Sims, Molycorp; personal communication).

With Permission of GoogleEarth (© 2012 Google) and USDA Farm Service Agency and © 2012 GeoEye

Figure 3-1. Molycorp Minerals rare earth mine, Mountain Pass, California.

Other mine sites around the conterminous United States and Alaska have produced REE-containing minerals in the past; however, the status of those sites is currently undetermined. A listing of known mines that have produced REE-mineral ores or REOs and locations where REE-containing mineral deposits have been discovered was compiled from Gupta and Krishnamurthy (2004), Orris and Grauch (2002), and Schuler et al. (2011) and is provided in ***Appendix B***. The only other significant REE mining operations are located in the Sichuan, Jiangxi, Shandong, and the Inner Mongolia provinces in China (Schuler et al., 2011); however, the Chinese REE mining operations and environmental practices are not considered applicable for comparative purposes in this report and are not discussed in any detail. In the absence of modern examples of mining activities for the extraction of REE ores in the United States, and considering the variability in the mineralogy and geology of known REE reserves, the following sections present a general discussion that introduces the life cycle of typical mining operations. The wastes generated during each mining stage that have the potential to cause environmental effects are also discussed, as applicable.

3.2 REE Ores

The REE metal is an elemental constituent of mineral REO ores. Concentrations of REE minerals typically occur in igneous and metamorphic rocks and also in sedimentary placer deposits. As discussed in ***Section 3.3.2.1***, concentrations of the target REO in the ore have implications for selection of the

mining method needed to obtain adequate quantities of the ore; the processing steps required (see ***Section 4***); and the volumes of wastes that must be managed.

The location of both hardrock and placer deposits in the conterminous United States and Alaska was discussed in ***Section 2***, along with the more common REE-minerals (i.e., bastnasite and monazite). The REE-containing minerals in a hardrock or placer deposit may or may not be viable for mining due to various reasons, including economic, technical, and environmental reasons, stemming from the concentration of the REE-bearing minerals in the host rock. The definition of an "ore" for the purposes of this document is as follows:

> ". . . a mineral source from which a valuable commodity (e.g., metal) is recovered. The term ore implies economic viability, given the concentration of metal in the host rock, the costs of extraction, processing and refinement, waste management, site restoration, and the market value of the metal" (U.S. EPA, 2008).

As the definition implies, the potential environmental impacts from all stages of a mine must be considered in evaluating the feasibility of the mine start-up—including the costs of mine restoration—to determine if a REE deposit represents an ore from which REOs and then REMs can be recovered economically.

3.3 Mine Permitting and Life-Cycle

Four life-cycle stages of a mine are generally recognized. These life-cycle stages include exploration, mine development, ore extraction and processing, and mine closure. Additional steps or phases are also incorporated within each stage. The activities associated with each stage can be considered as generally linear, but overlap is common. The time needed to complete each of the steps for mine startup depends on many factors and can potentially require many years before the mine is in full production.

3.3.1 Permitting Requirements for New Rare Earth Mines

A discussion of applicable mining regulatory policy and permitting requirements developed to manage the environmental impacts from mining operations is beyond the scope of this document. A detailed summary of applicable federal regulations can be found in the agency document *EPA and Hardrock Mining: A Source Book for Industry in the Northwest and Alaska* (January 2003: http://yosemite.epa.gov/R10/WATER.NSF/840a5de5d0a8d1418825650f00715a27/e4ba15715e97ef2188256d2c00783a8e/$FILE/Maintext.pdf). In general, projects with potential to have significant environmental impact are regulated under federal or state permitting programs. Mines developed near tribal lands require consultation with tribal leadership, especially if the mining activity or associated operations could impact the community or subsistence resources. As mentioned, mining operations on the scale that would be expected for recovery of REE minerals would potentially require large areas to accommodate an individual mine and its associated support facilities (e.g., waste material management areas and tailings ponds). This need for large areas of land often means that the land occupied by a mine is of mixed ownership and includes a combination of federal and private lands (National Academy of Sciences, 1999).

If a mining project is located on, adjacent to, or requires access and egress through federally managed lands, or has planned discharges to surface waters, then the permitting process is implemented under Section 102 of the National Environmental Policy Act (NEPA) [42 U.S.C. 4321 et seq.]. The life-cycle paradigm is typically used in the development of environmental impact statements (EIS) under NEPA for assessing the environmental impacts of a proposed mining activity on federal lands and this perspective will generally serve to frame the following discussion, which describes the mining life-cycle. The NEPA

process is not described in detail within this document, but can be found in *EPA's Hardrock Mining Source Book* (2003).

For general reference, known REE deposits that are located on or near federally managed lands are presented in Figure 2-2 and are tabulated in ***Appendix B***. States may also apply a NEPA-type process for permitting mining operations located within their boundaries, regardless of whether the mine property is located on federally managed lands.

3.3.2 Mining Life Cycle

Whether the environmental impact evaluation is performed under NEPA, state agencies, or through due diligence by the mining company, four life-cycle stages of the mine are generally recognized. These life-cycle stages are exploration, development (includes development planning, permitting, and construction), ore extraction and processing, and mine closure (includes shutdown, reclamation, and long-term monitoring). There are a number of steps that can be included within each of these mining stages that are briefly described below. However, the remainder of this section generally discusses the mining life-cycle stages, focusing on exploration and development phases and then ore extraction (i.e., mining) activities to remove rock or unconsolidated or semi-consolidated sediments (i.e., placers) containing the REE-mineral ores. Processing of REE-mineral ores and associated wastes is discussed in ***Section 4***.

It is important to recognize that there are not specific starting or ending points, or limitations, for these associated activities. Mining stages at a particular site can be cyclic and recur as mining operations progress. Exploration activities, for example, initially occur to evaluate the economic feasibility of the deposit, but then in-mine exploration generally continues once mining commences. Exploration activities may continue for less than a year, or may extend over a several years at a site until the economic viability of the deposit is determined. Once mining is underway, exploration work may progress beyond the mine, or in a near-mine area, to trace the extension and continuity of the ore deposit as the ore body is exposed during the mine advance. Reclamation activities are another example of how some mining operations are recurring during the life of the mine. These activities are also very site-specific and occur at various scales at the same site. Although areas of impact and the mass of earth materials resulting from exploration activities that require management are small in comparison to subsequent mine stages, some reclamation is often needed. Reclamation activities may be completed at the end of the exploration activity; occur intermittently as long-term exploration or mine advance continues; may not occur until mining is completed; or be initiated only after mining activities have ceased.

While the mining life-cycle is commonly discussed as definitive stages of activities inferring a linear temporal scale encompassing the life span of the mine, the previous examples illustrate how activities may occur and recur as phases or be on-going operations during the life of a mine. It is also important to understand that activities to prove a deposit or develop a mine may respond to external drivers, and that an active mine may stop operations for short or extended periods. Intermittent operations may be in response to seasonal conditions when the mine site is inaccessible due to weather extremes, or mine production may exceed the capacity of the processors to accept ore feed stock. Temporary stops in work (long and short term) may occur due to economic fluctuation in the price of the commodity, engineering failures associated with the mine or equipment, or technological issues (e.g., difficulty in controlling ground water infiltration; encountering complex geologic structure such as faults; and excessive depth of deposit). If mining activities are suspended, the permits and leases are often maintained in anticipation of resuming activities and operations at a later time. Mine sites generally close and are reclaimed only if pressured by the local community (e.g., due to poor safety or environmental record), the ore body has been exhausted, or if, due to technological issues, mining is no longer possible.

3.3.2.1 Exploration

Mineral exploration includes any activity performed to discover a potential ore reserve and determine the location, size, shape, position, and current economic value of the deposit. Prospecting, staking, sampling, assessment of mineral potential and economic feasibility, development plan, and permitting are all steps and activities that can be considered as part of the exploration stage. Prospecting employs non-invasive methods to evaluate the presence and characteristics of a potential deposit. Staking establishes mineral rights to develop the mine. An exploration step, using more sophisticated methods to delineate the deposit (e.g., geophysics), is followed by an intermediate stage of exploration that uses invasive methods (e.g., trenching, core or rotary drilling, bulk sampling) to sample the deposit. Samples are analyzed for metal content, and the data collected from the previous steps are used to create mineral potential maps showing the geologic favorability of the deposit; definition drilling is generally performed during this advanced stage of exploration. If the deposit is proven economically viable, then a mining development plan is drafted and applicable permits are obtained. These steps can also be considered as independent stages with exploration (i.e., use of invasive assessment methods) as one of these steps. As previously mentioned, the resource evaluation and scoping of the deposit can also be performed during the mine design stage. Baseline environmental studies may be conducted, if required, prior to exploration to determine the presence of sensitive species and habitat that might be impacted during these activities.

Permitting and regulation of these activities results from the interplay of state and federal agencies responding to their respective authorities and responsibilities. EPA's authority is invoked on matters of site assessment, financial responsibility, and future CERCLA related concerns. Examples of documents that can be requested or required in the permitting process include but may not be limited to: 1) documentation to address the requirements of the National Environmental Policy Act (NEPA), 2) National Pollutant Discharge Elimination System (NPDES wastewater discharge) permits for mining operations, 3) Underground injection control (UIC) permits for mining operations and 4) CERCLA financial responsibility documentation.

Exploration Methods

The approach and methodology used for exploration depend upon various factors, such as terrain, nature, and size of the target, and expected depth of the ore body; regulatory and permitting requirements and restrictions; available information and technology; and available capital resources. The intent of the exploration company (e.g., prove the deposit for sale, develop the mine) will also influence the scope of the initial exploration project and the approach and methods used to prove the deposit. The methods used may be very simple and low cost, or technically sophisticated.

The location of a proposed mine will also influence the extent and type of exploration activities that can occur. If the deposit is located in an existing mining district and/or on privately owned lands, then drilling permits may be more easily obtained by the exploration or mining company, and more aggressive exploration (e.g., exploratory drilling) may occur. If the site of the deposit is located near, for example, national forest lands, then exploration activities requiring land disturbance may not be allowed until a preliminary environmental information document (EID) is completed and undergoes EPA/NEPA review. Upon approval by the EPA or state agencies, drilling data can be collected and analyzed. The exploration data would then be used to inform additional environmental assessment that may be needed in the mine development-construction stage. The environmental impacts of exploration activities are sometimes overlooked; however, in many states, permits are required. An example (U.S. EPA, 2011b) is in the state of Alaska, where permits required for exploration activities include a Clean Water Act 404 permit for wetlands disturbance; camp permits; a temporary water use permit; an overland travel permit; land-use permits for off-claim camps or staging areas; bonds for staging fuel; hardrock exploration land-use permit; and a state bond pool requirement for reclamation. Drilling and trenching can be extensive, long-term operations using multiple types of heavy equipment with associated waste (e.g., used vehicle fluids,

lubricants and greases, solvents, other traditional industrial materials). Additionally, mining-type wastes (e.g., waste rock) can be produced during exploration activities and will need to be managed.

Passive Mine Exploration Methods

Examples of passive exploration methods applicable to rare earth deposits include common prospecting approaches (e.g., water, rock, soil, and sediment sampling; shallow pits) and geologic mapping and general field investigations. More sophisticated techniques employ geophysics, aerial and satellite remote sensing, mineral deposit models, and potentially other geochemical testing methods. The exploration team will generally attempt to identify geochemical and geophysical signatures that suggest the presence of the target REE-containing minerals; however, the response of geophysical techniques (such as magnetometer, radiometric, gamma-ray spectrometry, and remote spectral surveys) depends upon the mineral associations in the rock that accompany the REE-containing mineral deposits. Detailed spectral data from remote-sensing surveys can identify carbonate, ferrous iron, and REEs associated with thorium-rare earth element deposits (Armbrustmacher et al., 1995).

The commonly identified passive exploration steps do not generate many wastes and have little if any environmental impact. The one exception is ground-based geophysical exploration, which may require clearing through forested or other heavy-growth areas to accommodate larger truck-mounted equipment, resulting in an alteration of the terrain. Occasionally, earth-moving equipment may be used to remove soils and overburden or remove boulders that may be in the way of ground-survey activities. Soil and rock removed during exploration activities may be stockpiled onsite and used for onsite purposes or reclamation activities, as needed. As the exploration activity progresses, from more general information collection to more detailed data acquisition, ground surface disturbances generally are required. Additional access roads and drill sites are constructed to begin subsurface testing to sample from the mapped mineralized zone to further delineate and prove the resource.

Exploratory Drilling and Trenching

Data resulting from prospecting activities, geophysical surveys, geochemical surveys, and geological modeling are used to guide an exploratory drilling program to further substantiate and quantify the attributes of the ore body or target deposit, including its size, shape, and composition. These subsequent drilling programs can incorporate various types of tests. The drilling program seeks to determine the lateral and vertical extent of the REE deposit. Generally, rock cores are collected for further analysis to evaluate continuity of mineralization, grade, mineralogical relationships, rock types, and local hydrogeologic data. Rock strength testing and borehole geophysics may also be performed, and trenching may be used to collect bulk samples (i.e., several tons of material) across mineralized zones for metallurgical testing used to develop and evaluate processing methods that will be incorporated into the processing plant design. Large vertical shafts may be advanced to recover bulk samples or large tunnels or shafts that will accommodate large earth-moving equipment.

Exploratory drilling can be ongoing for long periods (i.e., weeks, months, or even years). The footprint of a single drill site may be a few hundred square feet in size, and there can be numerous drill locations. These operations can potentially disturb several acres of land to accommodate the drill sites, staging areas, and the onsite support facilities for the drilling operation. The spacing of drill sites is variable and dependent upon the continuity of the deposit. Exploratory borings may be drilled very closely spaced (i.e., 100 feet or less) or at larger intervals, depending on the characteristics of the site (National Academy of Sciences, 1999). Drilling boreholes to probe the REE deposit produces both waste solids and fluids. Rock flour or cuttings are removed as the borehole is advanced to greater depth. The nature and volume of cuttings produced at the ground surface depends upon the characteristics of the rock being drilled, the depth and diameter of the borehole, the presence of potable aquifers, and the drilling method. Rotary drills can require the use of a mixture of water and bentonite clays (i.e., a mixture often referred to as

drilling mud) as a drilling fluid to entrain and carry the cuttings to the surface while cooling the drill bit. Often, only water is used as a drilling fluid during exploration since clay drilling muds have the potential to complicate the petrologic and geochemical analyses; however, formation characteristics and the local hydrogeology may make drilling with muds or other additives necessary. Other rotary drills use compressed air to force the cuttings to the surface and keep the drill bit cool. Polymers, oils, or other synthetics are added to water or air flows to enhance the operational properties of the drilling mud or air, if needed. Prior to use, the drilling muds do not generally represent an environmental hazard and are either inert or break down quickly.

When the borehole intersects groundwater, the water can entrain materials from the borehold and transport those materials to the surface. The potential toxicity of these materials depend on the composition of any drilling fluids used and materials swept from the subsurface. These formation fluids can be highly mineralized, and the cuttings and drilling muds can entrain toxic levels of metals and other chemicals. Drill cuttings and drilling fluids are typically collected once the borehole is completed and abandoned; however, regulations in some states allow return of cuttings to the borehole. Excess materials may be stored in drums, contained in mud pits, or managed and disposed of as a waste.

Locations in the United States with Recent Exploration Activity and a Summary of Potential REE Resource Areas

Potential sites of REE resources have been under evaluation in recent years to prove the reserves and determine the mining potential at these locations. Sites receiving current or recent attention are located in Utah, Colorado, Wyoming, Alaska, California, Nevada, and Nebraska.

- During 2008, the Great Western Minerals Group, Ltd. completed an extensive drilling and sampling program at the Deep Sands deposit located in the Snake Valley and adjacent to the Deep Creek Mountains of west-central Utah. After a feasibility study to consider the low-grade monazite mineral ore containing rare earth concentrations, the company announced that it did not currently plan to undertake additional exploration at the site (Great Western Minerals Group, 2011).
- A recently formed company, Colorado Rare Earths Incorporated (CREI), announced in March of 2011 that it was soliciting funding to begin exploration near the Powderhorn mine site in Colorado (Colorado Rare Earths, Inc, 2011). CREI also has acquired properties at Iron Hill and Wet Mountains Colorado, where potential REE resources have been identified. CREI is currently organized as a mineral claims acquisition company, but plans to expand to an exploration and development company in the future.
- In Alaska, exploration is underway at the Bokan Mountain site that is located at the southern-most end of the Alaskan panhandle on Prince of Wales Island. This is a site that was mined in the past for uranium ore, but also has known HREE and LREE resources.
- Molycorp Minerals, as described earlier, is a past producer of REEs and is currently preparing to re-open its mine at Mountain Pass, California.
- In Nevada, about 16 miles east of the Mountain Pass mine, Elissa Resources is exploring multiple locations called the Thor REE Project Area, where HREEs and LREEs have been discovered; at least one of these locations is geologically similar to the Mountain Pass deposit (Elissa Resources, 2011). To date, Elissa Resources' exploration activities have included surface mapping, a district-scale detailed high-resolution airborne magnetic geophysical survey, extensive ground radiometric surveys, satellite imagery studies, petrographic studies, and sampling programs, including channel sampling and the sampling of historical surface workings that are remnants of a 1950s uranium-thorium prospecting rush.
- Quantum Rare Earth Developments Corporation recently has begun exploratory drilling at the Elk Creek Project in southeastern Nebraska. The focus of these drilling efforts is to perform a

resource assessment of niobium and associated REEs contained in a carbonatite deposit. These efforts are in the early stages, and no final determination about the resource has been made at this time (Quantum Rare Earth Developments Corporation, 2010).

- Bear Lodge Rare-Earth Project is located approximately 6 miles north of Sundance, Wyoming, and is comprised of 90 unpatented federal lode claims and one state lease, for a total of about 2400 acres. It is owned by Rare Element Resources through its Wyoming-incorporated Paso Rico (USA) Company, Inc. Twenty-three of the mining claims were obtained from Phelps Dodge Corporation and are subject to 2-percent net smelter return production royalty. The site has been prospected at various times since 1949. Several areas of mineralization have been identified, including high-grade copper, molybdenum, gold, and REMs within an altered carbonatite-alkaline-intrusive complex. Exploration efforts to date estimate that the rare earth resources at Bear Lodge could match or exceed the size and grade of deposits at Mountain Pass, California. The company web page reports that Rare Element Resources is currently exploring for rare earths and gold, and results have been very good to date.
- Pea Ridge mine (formerly owned by Upland Wings / Wings Enterprises. and currently owned by Pea Ridge Resources, Inc.) is a iron mine that has been in operation for about 40 years. The site is located in Missouri. The mine, under former ownership, had planned to produce HREEs as a byproduct from the iron ore body; however, mining of an adjacent ore body containing primarily REEs had also been planned (Wings Enterprises, 2011).. A mine feasibility study is underway (Pea Ridge Resources, 2012), but no information is readily available to determine whether or not REE will be produced.

The above locations are only examples of sites where some level of exploration activities have occurred, but others may exist. A general list of potential rare earth resource locations that have been documented in the United States is summarized in ***Appendix B***, which was compiled from a combination of sources. Other deposits likely exist or are being explored that were not identified or included in ***Appendix B***.

3.3.2.2 Mine Development

The term "mine development" is applied differently, depending on the region and entities involved. It is most often understood to be primarily a planning stage; however, it is also sometimes used to denote the construction phase, considering that planning has been accomplished during the exploration stage.

Feasibility Study

A financial analysis and corresponding feasibility study are important parts of this stage, as defined here, and are conducted considering the market value of the metal commodity, cost of production, characteristics of the deposit, and anticipated closure costs. The results are then used to determine if the deposit should be abandoned (i.e., not likely to ever be an economically viable deposit), should remain idle (i.e., could become economically viable in the future), or if development of the deposit is economically feasible and should proceed. Typically, a feasibility study for a medium-size mine requires 3 to 4 months and, for larger projects, 6 to 9 months (De la Vergne, 2003). Concerns for the environmental effects of the proposed mining activity, and associated mine areas must be considered relative to long-term costs. The potential impacts to the immediate property, adjacent lands, and surrounding community are identified, and additional baseline environmental studies may be performed or continued during this stage. Investors may be sought using the results of the feasibility study.

Mine Plan

The layout and design of the mine is performed to locate stockpile areas and waste areas where these can be best managed to prevent or minimize environmental damage. Engineering design and environmental assessment should be conducted in tandem so that collected and measured data can mutually benefit both

purposes and allow for collaboration of engineers and environmental scientists; however, while this is best practice, the approach is sometimes not used due to inadequate planning or logistical difficulties. Mitigation measures can then be addressed more efficiently through management plans and compensation measures that are integrated into the feasibility models to evaluate costs.

REEs commonly occur in ores that also contain uranium and thorium. Ores containing the REE-bearing mineral monazite are particularly high in concentrations of thorium (Long et al., 2010). Uranium also occurs in or with ore deposits that contain REE-bearing minerals. The amounts of radioactive elements in the ore is not dependent upon the mineral type specifically, but more on the petrogenesis of the deposit containing the ore. In general, nearly all rocks, soils, and water contain small amounts of radioactive materials, such as uranium, thorium, radium, radioisotopes of potassium, lead, polonium, and their decay products. When naturally occurring radioactive materials (NORM), in their undisturbed natural state, become purposefully or inadvertently concentrated, either in waste by-products or in a product, they become technologically enhanced naturally occurring radioactive materials (TENORM) (U.S. EPA, 1999).

Waste areas containing high concentrations of uranium and thorium require complex management. Management begins at the mine design stage, where the mining methods and milling plant processes are planned to optimize a waste reduction-minimization strategy. The treatment of tailings is a significant safety concern, as well as an environmental issue. The EPA reports (U.S. EPA, 1999) that the radiation levels from waste rock and sludges associated with the production of REOs range from 5.7 to 3,224 pCi/g. Additional treatment circuits are generally required to precipitate radium from tailings, and additional controls are needed to manage radon. Production and management of radioactive mining and milling wastes is tightly controlled by national (including the Safe Drinking Water Act, Clean Water Act, Comprehensive Environmental Response, Compensation and Liability Act [CERCLA], and Clean Air Act) and state regulations, and if REE is produced with commercial uranium or thorium, then international protocols and agreements also may apply. Information pertaining to laws and regulations that apply to TENORM can be found at EPA's Radiation Protection website (http://www.epa.gov/radiation/tenorm/regs.html). The challenge is generally balancing the human health and environmental risks with production costs. The issues associated with these materials can affect the feasibility and viability of a proposed mining project, especially when addressing plans to reopen older mining sites. Tighter regulation on the use of radioactive minerals has been identified as the primary factor that pressured many sources of monazite out of the REEs market during the 1980s (Long et al., 2010).

Processing these ores containing radionuclides subsequently increases the concentration of naturally occurring radioactive materials, and the levels of radioactivity can become higher than background levels near waste management areas. However, it should be noted that radioactive wastes from mining and milling operations are not the same as waste containing special nuclear materials that are associated with the production of enriched (i.e., increased concentrations of highly radioactive isotopes) radioactive materials generated by nuclear fuel cycle facilities or disposed of by nuclear power plants. The principal issue at mining and milling sites is the volume of wastes containing natural radioactive elements that are produced and managed.

Environmental Studies

This section is presented for general background and to provide some perspective of the complexity of mine siting studies under NEPA; however, the information presented here should not be considered as guidance, nor should it be taken as a comprehensive discussion of the types of environmental assessment activities that may be required.

In general, if mines are located on or adjacent to federally managed lands or will have discharges to surface water then an Environmental Information Document (EID), also known as an Environmental Study or Environmental Report under some programs, is required under NEPA. Preparation of this report is generally performed by the proponent during early mine stage activities as the viability of the mining operations is being assessed. The EID describes the project, characterizes the environment that potentially may be impacted by the mining activities (including cumulative impacts), assesses the potential severity of any impact, identifies mitigation measures to avoid or lessen the impacts, and discusses alternatives for methods and operations, that may include an evaluation of the critical need of the commodity (e.g., availability of the commodity from other markets, substitute materials, or recycling). Information from the proponent's EID is used by the managing agency for the project to prepare an Environmental Assessment (EA) report describing the potential for environmental impact and the preferred alternative. If the mine project is considered a major federal action that has the potential to significantly affect the quality of the human environment, then the EID and/or EA is used by the lead government agency to develop an Environmental Impact Statement (EIS); however, additional environmental baseline and engineering studies may be needed. The EIS is then reviewed by EPA and other agencies, if applicable, as part of the NEPA process to determine if unavoidable adverse impacts will occur, and if irreversible and irretrievable commitments of resources are likely, considering connected actions, cumulative actions, and similar actions. A period of public review and the issuance of a Record of Decision (ROD) follows. If an EIS is implemented, monitoring is required for any mitigation steps required and implemented.

Common baseline studies performed to support the EID might include an evaluation of aquatic resources (including wetlands), terrestrial habitat, ground water quality and supply, air quality, and human population and demographics. Each of these studies focus on characterizing the environment that potentially may be affected by the operations and activities at the site. The information from baseline studies is then used in the EID to assess the potential impact that the operations and activities may have on the site and surrounding environment, relative to the potential impacts identified and anticipated for the mining method used and the associated operations and processes. Impact may include degradation of habitat or habitat alteration or loss; however, in some special cases, habitat may actually be enhanced or created. Water use for mining operations may also cause flow alterations that have adverse impacts to aquatic habitat, or in-stream structures used for water control may obstruct fish movement, migration, and spawning patterns. An aquatic resource study generally evaluates the distribution, abundance, and condition of fish species, benthic macroinvertebrates, and amphibians, along with the distribution and extent of the habitat and riparian zones. To assess existing stress on the aquatic environment, water quality criteria are evaluated against the actual condition of the water body, and toxicity studies and metric analysis of macroinvertebrates may also be performed. Aquatic impacts from mining and mine processors are often considered to be the most significant.

Milling and processing operations are sometimes shared by multiple mines, and ore must be conveyed to the mill or processor site. The impacts to health and safety from the method used for ore conveyance, often by heavy truck or railway, through in-route communities and sensitive areas must be considered in relation to existing traffic patterns, spillage of loads along routes, and the degradation of air quality. This generally includes the release of windblown air particulates and vehicle exhausts. However, in addition to air particulates, other studies may be necessary to evaluate the potential impacts from stationary and mobile sources of air emissions that could emit any of the hazardous air pollutants (HAPs) that are regulated under the Clean Air Act.

In order to determine the severity of potential impacts to nearby human receptors, a population study is usually performed. Land-use mapping is also a common analysis performed to aid with population studies and to help identify farming areas, parks, schools, hospitals, and other potentially sensitive areas (both human and ecological habitat) adjacent to the proposed mine site. Evaluation of local demographics is generally performed to insure fair treatment of racial, ethnic, and socioeconomic groups.

NEPA stipulates that 3 months may be needed for review of an EID, but that a longer period may be required. NEPA also describes the preparation of the EIS and the intra-agency review process as potentially requiring 12 months or longer. Therefore, there could be a period of several years between initial exploration steps and startup of a REE mine that is located on federally managed lands. If needed, land, mineral leases, and all regulatory permits would be acquired pending acceptance of the EIS. Any environmental audits required would also be performed.

The USGS (2011) evaluated the time it took to develop metal mines that opened in the United States since 2000. It was found that even if expedited permitting occurs, the period to obtain a permit could take 7 years. It was also found that periods of 1 month to 17 years may be required before commercial production. Ramp-up times for new mines might take from 2 to 12 months.

The typical time frame for a mine project from prospecting (i.e., initial exploration) through construction of the mine was generalized by EPA Region 10 and is presented in **Figure 3-2**, below (U.S. EPA, 2011b).

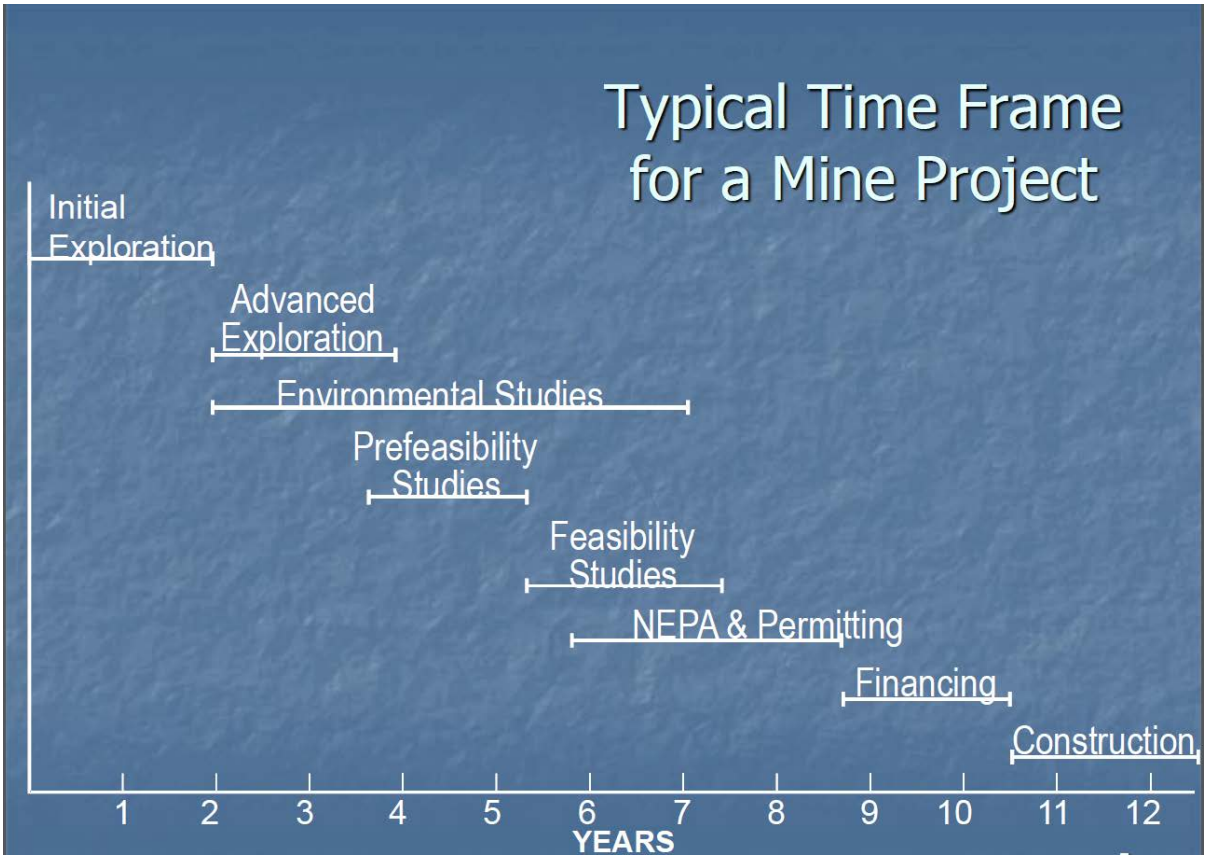

Figure 3-2. Typical time frame for a mine project.

There are numerous factors that affect the time required for mine development. Some examples might include the location of the mine (e.g., federal lands, state lands, or private lands and greenfields versus brownfields); geologic complexity of the site; metallurgical complexity of ore; level of stakeholder involvement; availability of required infrastructure; and experience of regulatory authorities with mine type and area where deposit is located.

Financial Assurance Requirements

Mining companies must also provide for financial assurance that the mine site will be restored to a condition that does not represent a risk to the environment or human health. The federal Superfund law, also known as the CERCLA, contains a provision that requires EPA to establish financial assurance requirements for facilities that produce, treat, store, or dispose of hazardous substances. Under CERCLA, a wide range of elements, compounds, and waste streams are specifically designated as "hazardous substances" in Title 40 of the Code of Federal Regulations, Section 302.4. Many states have established financial assurance requirements that are in place; however, the CERCLA 108(b) financial assurance regulation for hardrock mining currently implements section 108(b) of CERCLA (42 U.S.C. 9608(b)(1)), which directs the President to promulgate requirements that

> "…classes of facilities establish and maintain evidence of financial responsibility consistent with the degree and duration of risk associated with the production… treatment, storage, or disposal of hazardous substances."

As of the issuance of this report, the EPA is currently working on a methodology that will be used to determine the level of financial responsibility requirements that will be imposed on the mine or mine facility owner under Section 108(b) of CERCLA.

EPA's responsibilities in this area are defined by the federal Superfund law also known as CERCLA. CERCLA contains provisions that give EPA the authority to require that classes of facilities maintain financial responsibility consistent with the degree and duration of risk associated with the production, transportation, treatment, storage, or disposal of hazardous substances.

Current and Prospective Mine Development Activity

Rare earths are often a constituent in ores processed to recover other metal or mineral commodities. The demand for rare earths may create opportunity for these mines to consider expanding their operations to produce rare earths in addition to their primary commodity. Expansion of mining operations and changes to milling and processing operations may require environmental review and additional permitting for these active mining operations.

In addition to rare earth production from current mining sites, it could become profitable for operations to resume at former mine locations. These may be mines with active permits that are currently not in operation due to the current market value of the principal commodity mined, or closed mines where ore remains but no mining is occurring, equipment has been removed, and possibly some level of reclamation has been started or completed. Stockpiles of subeconomic ore, or potentially the waste tailings, may now represent a rich source of ore for REEs that can help the mine transition back into production as the mine site is re-developed. Most of the prospective REE mines in the United States include those that produced REE ores in the past (e.g., Molycorp Mineral's mine in Mountain Pass, California) or produced another commodity from an ore containing REEs (e.g., Pea Ridge iron ore mine). Some exploration may be required, or enough existing data may be available to begin planning the re-opening of the mine. Most of the activities required for the mine development stage will be needed to reopen the mine. In some cases, the environmental impacts from past mining activities and practices will need to be considered in development of the new mining operation.

Development activity is currently occurring at two locations in the conterminous United States to reopen idle mines. These include the Molycorp mine in California (as previously discussed) and the Pea Ridge mine in Washington County, Missouri. Pea Ridge is a $1 billion dollar project that is underway in Missouri to reopen the existing Pea Ridge mine and to begin construction of a processing plant for magnetite iron ores (Baranyai, 2011). The iron ore processing plant will be located 1 mile from the mine, and ore will be pumped through a pipeline to the plant. A St. Louis-based company (Wings Enterprises,

Inc.), with support from Glencore International AG of Baar, Switzerland, was developing plans around the opening of the Pea Ridge Mine, and, in early 2012, had expected to start producing rare-earth minerals from holding ponds left by previous mining activity and also from newly mined ores (Wings Enterprises, 2011). Wings Enterprises had estimated that underground mining may extract as much as 5,000 tons of rare earths in 3 years. In addition to construction activities, planning and feasibility studies were under way for the joint iron ore and REE mining operations in Missouri. However, Pea Ridge Resources, Inc. recently purchased the mine from Upland Wings/Wings Enterprises. No additional information was provided on the company's website to determine when or if REE resource planning and/or production will resume or continue (Pea Ridge Resources, 2012).

3.3.2.3 Construction and Mining (Mineral Extraction)

Once regulatory approvals have been acquired, construction can begin on waste management and processing areas, followed by the commencement of mining activities. The mining methods that might be used to recover REE ores are not different from hardrock or placer mining operations used for extracting other metal ores. The EPA defines a hardrock mine in accordance to the BLM definition:

> "(as extracting) Locatable minerals that are neither leasable minerals (oil, gas, coal, oil shale, phosphate, sodium, potassium, sulfur, asphalt, or gilsonite) nor saleable mineral materials (e.g., common variety sand and gravel). Hardrock minerals include, but are not limited to, copper, lead, zinc, magnesium, nickel, tungsten, gold, silver, bentonite, barite, feldspar, fluorspar, and uranium (BLM, 1999b). Usually refers to rock types or mining environments where the rocks are hard and strong and where blasting is needed to break them for effective mining."

Placer mining and placer deposits are generally defined (U.S. EPA, 2011d) as

> "The extraction of a mineral deposit that has achieved its present distribution through the prior action of moving water or wind. Placers are usually in poorly consolidated materials and are the sources of much, but not all, tin, titanium, rare earths, diamonds, and zirconium, and some gold."

Hardrock mines are typically either aboveground or underground operations. Solution mining techniques could also be used to extract REM oxides from the subsurface; however, the use of solution mining is unlikely in the United States due to the potential for environment impacts and the absence of suitable deposits. Solution mining is one of the principal mining methods currently used in China to recover REEs from clay deposits. Placer deposits are typically near-surface deposits that extend over greater areas rather than to great depths.

The method of extraction is dependent on the grade of the ore; size of the deposit; ore body position (i.e., the size, shape, dip, continuity, and depth); geology of the deposit; topography; tonnage, ore reserves; and geographic location and is based on maximizing ore recovery within economic constraints. A low-grade cutoff point is established on a site-specific basis and depends on recovery costs at the site, the market price of the ore, and feed requirements at the mill. It is not uncommon for open-pit and underground mining to occur at the same site. Mine pits at aboveground mines are generally conical in shape, with the diameter decreasing with increasing depth; however, a conical pit is not always developed, and the advance of some aboveground mines are controlled by topographic and/or geologic features. Eventually, there may no longer be adequate room for equipment to work safely in the pit, and it may not be feasible or practical to remove additional waste rock to widen the pit. After that point, an underground mine may be developed inside the lower reaches of the mine pit to reach deeper parts of the deposit. The economics of widening the pit may also make mining of deeper sections of the ore body using underground methods more advantageous. The more common mining methods are described below.

In Situ Leach Mining

It is unlikely that in situ leach (ISL) mining methods would be used in the United States to recover REEs. Limited geologic conditions suitable for ISL, environmental concerns associated with the strong acids that would likely be needed, and the low solubility of REEs likely preclude ISL from being considered as a viable method for recovering REEs from deep ore deposits. However, this method is presented here because ISL has been used in China and in the United States for other metals.

Very simply, ISL mining injects a fluid (i.e., water, acids, or other chemicals) into a circuit of drilled boreholes intersecting the mineralized zone, and then an enriched or saturated solution is pumped from the ore containing the target metals. The enriched or saturated solution is then processed, typically with a solvent extraction method, to recover the metals. This method has been used for mining copper and uranium in the United States on a limited scale. Copper ore dumps around formally active underground copper mines have also been mined using similar techniques, and REEs are known to occur along with some copper deposits (e.g., Bear Lodge, Wyoming). Although it is thought to be unlikely, use of ISL might be considered as an alternative to recover REEs from abandoned shafts backfilled with subeconomic ore, dredge wastes of former mines, or from the waste of active mines producing other commodities from ores containing REE. The hydrogeologic conditions must be suitable for in situ mining to be successful and also environmentally safe. Because in situ mining does not cause the level of ground disturbance that either aboveground or underground mining does, due to the lack of waste piles and ore stockpiles, it is sometimes initially considered as an alternative mining method in the NEPA process during the mine development stage.

In situ mining is typically used where the mineral or metal deposit is very deep underground and also where there are lower grade ores. The success of the method depends of the solubility of the target metals, geochemistry, and hydrologic characteristics of the ore. Solution mining of shallow deposits (e.g., placer deposits) is also possible, but using this approach risks contaminating an aquifer suitable as a drinking water source or that is in direct hydraulic connection with and recharging a surface water body or the marine environment. Chemicals used for leach solutions and leachate solutions containing concentrated metals and other salts must also be managed and stored. Strong chemical reagents would likely have to be used to recover the REEs from the rock or waste materials so the environmental risk is likely too high for this to be a viable method. Due to environmental concerns associated with this mining method, solution mining would likely have limited application for the recovery of REMs in the United States.

Surface and Underground Mining

Underground and open-pit mining are the more conventional methods used in the hardrock mining industry. Both of these more familiar mining methods produce common wastes; however, the environmental impact from underground mining is generally considered to be potentially less due to minimized land disturbance, targeted mining producing less waste rock, and differences in handling practices for the rock waste, although there are likely exceptions to this generalization. Underground mining is generally more expensive, primarily due to the lower production rates possible at higher cost compared to aboveground methods. Additional safety measures are also usually required for underground methods that increase operational costs.

An example of an open-pit mine is the Molycorp Minerals rare earth mine in Mountain Pass, California (see Figure 3-1, above). The mining operations at Pea Ridge, Missouri, are extensive and deep underground mining works. An aerial view of the Pea Ridge mine is provided in **Figure 3-3**.

Attribute Google (© 2011 Google) and USDA Farm Service Agency

Figure 3-3. Aerial image of Pea Ridge magnetite mine, Missouri.

Open-pit mines use a variety of drilling, earth-moving equipment, and explosives to terrace into the subsurface to extract overburden, waste rock, and ore. Underground mine operations are more targeted, but also use drilling, excavation equipment, and explosives to construct a series of shafts that advance to and then remove ore to the surface. Because of their typically elongated nature, geochemical deposit models suggest that both thorium-rare earth element veins and carbonatite dikes could be developed by underground mining techniques (Armbrustmacher et al., 1995). The depth and extent to which open-pit or underground works are advanced depends upon the ore grade, nature of the overburden (e.g., thickness and hardness, or difficulty of removal), and the stripping ratio. Stripping ratios of overburden to ore can be large (e.g., 80:1) for aboveground mines and much smaller for underground mines (e.g., 1:1 to 1:20). Stripping rations for open pit uranium mines range from 10:1 to 80:1 with an average of around 30:1 (USEPA, 1983b, Vol. 2). The stripping ratios also illustrate that the potential of environmental impact from rock waste is generally much less from underground mining operations.

Both methods produce overburden piles, piles of waste rock, ore and subgrade-ore stockpiles, and sediment. Overburden piles that contain soil and non-ore-bearing (or non-mineralized) rock, removed to expose the mineralized ore body, are produced during aboveground and underground mining operations. Overburden is typically stored separately from other stockpiles and wastes because it can contain less of the deeper mineralized rock of the ore body. Overburden may also be stored from the development of underground mines or used to backfill mine shafts as mining progresses; however, the volume of overburden and waste rock is typically less from underground mines. Waste rock piles store more mineralized rock that was removed from around the ore body. The differentiation between waste rock and ore can be relative and dependent upon economic variables.

Placer Mining

Placer deposits are accumulations of mineral or metal-bearing alluvial sediments that have accumulated in depressions or stream beds. Placer mines are not considered hardrock mining because the REE ore is recovered from unconsolidated alluvial or colluvial deposits; however, these mines are often grouped with hardrock mines for regulatory purposes because the REE host minerals can present the same processing challenges as those mined directly from a rock ore body.

Placer mining includes the classic image of a gold miner using a pan or a sluice box. Larger and more modern operations may excavate an open-pit or tunnel into ancient riverbed sediments. Excavation might be achieved using water pressure (hydraulic mining), excavation or tunneling equipment, or dredging equipment that is used to mine ore-bearing sediments from stream beds or depressions. Native gold deposits, uranium, thorium, zirconium, and mineral ores for REMs are examples of placer ore deposits that occur in the United States. More REE mineral ores have been discovered associated with placer deposits in the United States than any other deposit type (see **Table 3-1** and ***Appendix B***). The Vero Beach mine in Florida and the Old Hickory mine in Virginia are examples of placer mines that had produced REEs as a by-product of zirconium mining in the past. The Old Hickory mine continues to operate, but currently is not producing REE-containing minerals (ILUKA Resources, Ltd, 2007). Placer deposits containing monazite REE-mineral ores are typically associated with higher concentrations of minerals containing radioactive elements, which has deterred production from these deposits in the United States.

Prospective Mine Types by State

A general summary indicating the number of potential rare earth mining sites (i.e., potential resources) that have been documented in the United States is summarized in **Table 3-1**. Data were summarized from the table in ***Appendix B***, which was compiled from a combination of sources, but is principally from information available from the U.S. Geological Survey. The table is presented not to suggest that every known deposit will be exploited, or that there is potential viability for the rare earth resources that occur at these locations. It is provided simply to assist stakeholders in these states gain an awareness of the level of known occurrences of REE resources. Other deposits and mine sites likely exist or are being explored that were not identified or included in ***Appendix B***; however, the following table gives a general idea of types of mines that might be found or developed in each state. It should be noted that this information is very general; no aspects of the mine sites have been verified, and the current condition of the mines listed is largely unknown. Actual data were available for some existing mines, but the mine type for a few of the mines listed was inferred from the deposit types or information found on the Internet; approximate counts are shown in parentheses.

In large part, the table illustrates that the majority of discovered REE deposits, documented in the information sources found, would be mined as placer deposits or from aboveground open pit mine types. Neither the Molycorp or Pea Ridge mines, previously discussed, that are being developed and are near production stage are the more common placer deposit (i.e., dredge type mining) operations, but rather the Molycorp mine is an aboveground mine and the Pea Ridge mine is an underground mine. As previously discussed, the feasibility and viability of a deposit depend on a number of complex variables.

Table 3-1. Numbers of Existing Mines by State Where Potential REE Resources Have Been Reported (see Appendix B for References)

State	Placer Mine or Sedimentary Deposit[a]	Open Pit or Underground - Unspecified[a, b]	Existing Open Pit	Existing Open Pit with Underground Works	Existing Underground Mine	Total Mines/ Deposits by State
Alaska	(9)	(5)	1	0	0	15
Arizona	0	(2)	0	0	0	2
Arkansas	0	1	0	0	0	1
California	(1)	2	1	0	0	4
Colorado	0	(3)	1	0	0	4
Florida[c]	2, (4)	0	0	0	0	6
Georgia[c]	1, (4)	0	0	0	0	5
Idaho	7,(15)	(2)	4	1	0	29
Illinois	0	(1)	0	0	0	1
Missouri	0	0	0	0	1	1
Montana	0	1, (3)	0	0	0	4
Nebraska	0	(1)	0	0	0	1
Nevada	0	1	0	0	0	1
New Jersey	0	0	0	0	1	1
New Mexico	0	(6)	4	1	0	11
New York	0	0	0	0	1	1
North Carolina	1, (1)	0	0	0	0	2
Oregon	0	(1)	0	0	0	1
South Carolina	1, (2)	0	0	0	0	3
Tennessee	1, (5)	0	0	0	0	6
Texas	0	1	0	0	0	1
Utah	(1)	0	0	0	0	1
Virginia	1	1, (1)	0	0	0	3
Wyoming	(5)	(5)	0	0	0	10
Totals:	61	37	11	2	3	113

[a] Numbers in parentheses indicate that a record of an existing mine was found, but that the type of mine was not specified; numbers in parentheses are known occurrences.

[b] Mines assigned to this category are for igneous or metamorphic deposits and not placer or sedimentary deposits.

[c] A few mines extend across state boundaries between Florida and Georgia.

3.3.2.4 Mine Closure

The closure of a mine refers to cessation of mining at that site. It involves completing a reclamation plan and ensures the safety of areas affected by the operation; for instance, by sealing the entrance to an abandoned mine. EPA requires that planning for closure is ongoing for mines located on federal lands and not left to be addressed at the end of operations. The Surface Mining and Control Act of 1977 states that reclamation must

> "restore the land affected to a condition capable of supporting the uses which it was capable of supporting prior to any mining, or higher or better uses."

In some cases, reclamation may not be possible to a level that would support past uses, and long-term monitoring and management may be required.

Mines close for a variety of reasons, including economic factors due to a decline in the market value of the metal; geological factors such as a decrease in grade or size of the ore body; technical issues associated with geotechnical conditions, such as mine stability or in-rush of ground water at rates too high to manage; equipment failure; environmental impacts; and community pressures (Laurence, 2003).

Often, mines will not close but rather become idle, with plans for reopening when the market will support the venture. Idle mines can continue to cause a variety of health-related hazards and threats to the environment if not properly managed. While the mine is idle, the waste piles, the tailings ponds that are associated with the processing plant, and other mine areas must be stabilized and managed, potentially over many years.

Mines can be adequately managed to avoid log-term problems; however, the pollution and contamination issues that generally require environmental management over the life of the mine can remain after mine closure, such as the following:

- Sedimentation of surface waters
- Effluent and drainage (e.g., due to heavy precipitation during the rainy season and snow melt) from the mine, storage piles, or tailings management areas that can impact downstream drinking water sources and aquatic habitat
- Acid mine drainage (AMD) and enhanced acid rock drainage (ARD) that also effect aquatic habitat
- Continued pumping of mine water and contaminant plume migration control pumping that causes drawdown of nearby aquifers
- Contaminated dusts
- Subsidence or collapse of tunnels and subsurface structures, which also represents a safety hazard
- Hazardous materials remaining on-site (e.g., fuels, lubricants, other chemicals).

These management activities must be planned for long after operations cease and the mine is closed. The risks associated with these impacts are discussed in ***Section 6***.

In the case of public lands the state or a land management agency has the final authority for concerting various regulatory authorities and overseeing mine closures. For example, EPA's responsibilities may include but not be limited to; NPDES wastewater discharge permits for post-closure mining operations, Clean Water Act (CWA) and Resource Conservation and Recovery Act (RCRA) related permits required for wastewater or contaminant treatment options (if necessary), and CERCLA financial responsibility documentation.

3.4 Characteristics of Mining Waste Sources

Mining wastes could be referred to as (managed) materials of concern and, in general, some materials are not considered wastes until a particular time in their life cycle. However, that is not to imply an absence of environmental risk from stockpiled or stored materials. Mined materials that are generated may only occasionally or periodically be managed as wastes. Often, these materials are used for various onsite or offsite purposes instead of being stored as wastes, although the volume of waste material can often exceed the demand for reuse alternatives.

EPA evaluates the risks to human health and the environment from reuse of various types of industrial sector wastes, including mining; however, many of these studies are ongoing, and this report does not

specifically address reuses or reuse issues as they relate to mining wastes from hardrock mining operations (e.g., REE mines). Reuse of mine wastewater is a common practice. The wastewater is removed from underground workings or open pits and then re-circulated for onsite use (e.g., processing areas) or even offsite use if the water is of adequate quality. However, these waters must meet discharge limits for concentrations of metals or other constituents and also be permitted for discharge to surface waters. Unless it represents a problematic waste, rock waste materials may be used as aggregate for a variety of onsite and offsite construction purposes. These might include uses such as base material for building foundations, road beds, retaining structures, or other purposes. Many of these reuse strategies encapsulate waste-rock material, effectively separating it from atmospheric influence that would cause a release of toxic metals, acids, or alkaline waters to the environment.

3.4.1 Soil Storage Piles

The soils removed during the construction-mining stage of an aboveground mine site are typically placed in a storage pile and may be used during restoration at the end of the mine's life. Soils are typically not considered wastes but can be a potential source of pollution if not properly managed, especially for providing a source of sediment in runoff. Humus-rich soils may be acidic, and fines that run off to streams could affect surface water quality. Acidic soils used as cover for metal-bearing rock-waste areas could encourage metal leaching from the rock.

3.4.2 Overburden

Overburden storage piles of sediments and rock materials that do not contain the commodity can include other metals and constituents that may also be a source of pollution and contamination. While relatively small in comparison to quantities of other mining waste, overburden, which is the material removed to expose the ore during mining, may include unconsolidated materials such as alluvium, colluviums, glacial deposits, or residuum and be a source of sediment or acid-generating minerals; however, the acidity of these materials is usually low and they generally do not contain significant concentrations of metals. Overburden usually does not include rock that contains the mineral ore, but it may include the very low mineralized rock removed from around the ore from hardrock mines. These materials can contain greater metal concentrations than typically associated with unconsolidated deposits. Without proper management, erosion of the overburden storage piles resulting in sediment loading to streams and surface water can occur. Ground water may be entrained with the overburden material, which can then leach through to the base of the pile, carrying with it high concentrations of metals and other potentially harmful constituents. Overburden piles can cover hundreds of acres and be a prominent feature in the general landscape as they reach heights extending hundreds of feet. Large mines may have multiple overburden storage piles. Large mine trucks and other vehicles deliver materials to the top of the pile and shape the slopes. Fugitive dusts are a concern from overburden storage piles.

3.4.3 Ore and Subeconomic Ore Storage

Ores may be stockpiled to provide a supply, lasting 6 months or more, of ore stock feed for beneficiation and processing plants. Subeconomic ore is often stockpiled at the mine site for future exploitation under the appropriate economic or market demand conditions. These ore stockpiles and subeconomic ore storage piles can include large areas. Mines may stage ores at multiple sites. Ore stockpiles can represent a significant source of toxic metals. Runoff, flooding, or infiltration of rainwater, if not captured and managed, can have significant effects on aquatic habitat. Ground water may be entrained with the ore material, which can then leach out to the base of the pile, carrying with it high concentrations of metals and other potentially harmful constituents. Large mine trucks and other vehicles deliver materials to the top of the pile and shape the slopes. Fugitive dusts containing metals or other harmful constituents from the ore and subeconomic ore stockpiles, even though not as much of a concern as tailings wastes or conveyances, may still be of potential concern depending upon the material stored.

As previously discussed, AMD is uncommon in most REE deposits; however, some potential exists for low levels of acid generation from accessory minor sulfide minerals, especially in low-Ti iron oxide Cu-U-Au-REE deposits like Pea Ridge (Foose et al., 1995). Carbonatite ores, such as those at the Mountain Pass mine, may cause elevated pH in streams, depending on the concentration of other acid-producing accessory minerals in the ore-bearing rock and surrounding country rock that can serve to neutralize any runoff. Thorium-rare earth element veins have moderately high sulfur content, but the sulfur is present chiefly as sulfate in barite. Sulfide mineral content of these vein deposits is very low, thus potential for AMD generation is low (Armbrustmacher et al., 1995). Carbonatites are important REE ores, and these igneous rocks contain greater than 50 percent carbonate minerals. Waste rock from REE deposits could potentially present a problem with neutral mine drainage (NMD), with pH in the range of 6 to 10. Mine drainage in the NMD pH range can have various elevated metal (e.g., zinc, cadmium, manganese, antimony, arsenic, selenium) concentrations (INAP, 2010). In the case of REE deposits, there is generally a lack of a mineralogical source for metals that are mobile under such conditions; however, elements like uranium and vanadium could be mobile under NMD conditions, and these elements are constituents of some REE ores. Special engineering designs, waste handling and disposal procedures, or closure and reclamation plans may be required for those materials whose characteristics may pose significant risks. The impact of AMD depends upon the ability of receiving waters (ground water and surface water) to neutralize and dilute the drainage.

3.4.4 Waste Rock

The following description of waste rock is adapted from *EPA and Hardrock Mining: A Source Book for Industry in the Northwest and Alaska* (U.S. EPA, 2003). Waste rock is removed from above or within the ore during mining activities. It includes granular, broken rock, and soils ranging in size from fine sand to large boulders, with the fines' content dependent upon the nature of the geologic formation and methods employed during mining. Waste rock consists of non-mineralized and low-grade mineralized rock. Materials may be designated as waste because they contain the target minerals in concentrations that are too low to process, because they contain additional minerals that interfere with processing and metals recovery, or because they contain the target metal in a form that cannot be processed with the existing technology. These materials are stored as waste at one point in a mine's life, but may become ore at another stage, depending on commodity prices, changes in and costs of technology, and other factors. Waste rock and subeconomic ores may be stockpiled together or separated in grades of material.

Similar to ore/subeconomic ore stockpiles, waste rock storage piles are typically large, covering acres of land and extending to a height of many feet. Waste rock piles can represent a significant source of toxic metals. Runoff, flooding, or infiltration of rainwater, if not captured and managed, can have significant effects on aquatic habitat. Ground water may be entrained with the waste rock if the rock units being mined occur below the water table, which can then leach out to the base of the pile, carrying with it concentrations of metals and other potentially harmful constituents. Large mine trucks and other vehicles deliver materials to the top of the pile and shape the slopes. Fugitive dusts containing metals common to the ore material are also a concern from waste rock storage piles. **Figures 3-4 and 3-5** present block flow diagrams of conventional hardrock and placer deposit mining, materials management, and potential pollutants.

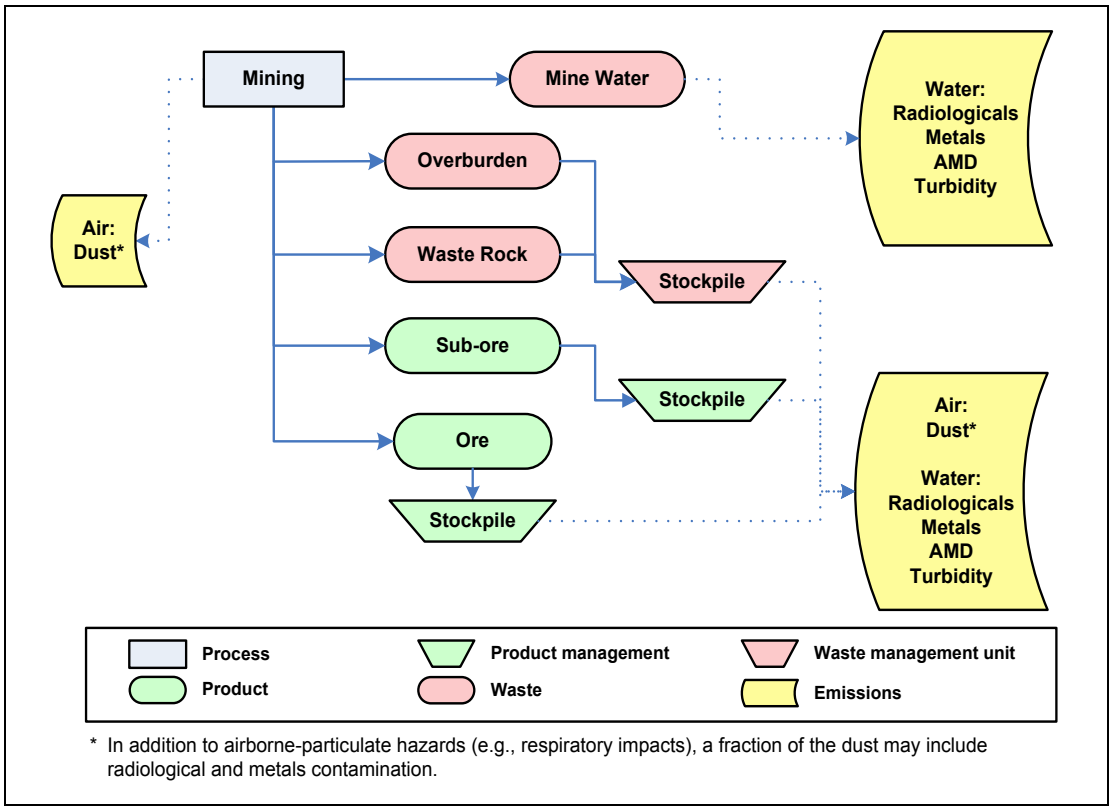

Figure 3-4. Conventional hardrock deposit mining process and wastes emissions.

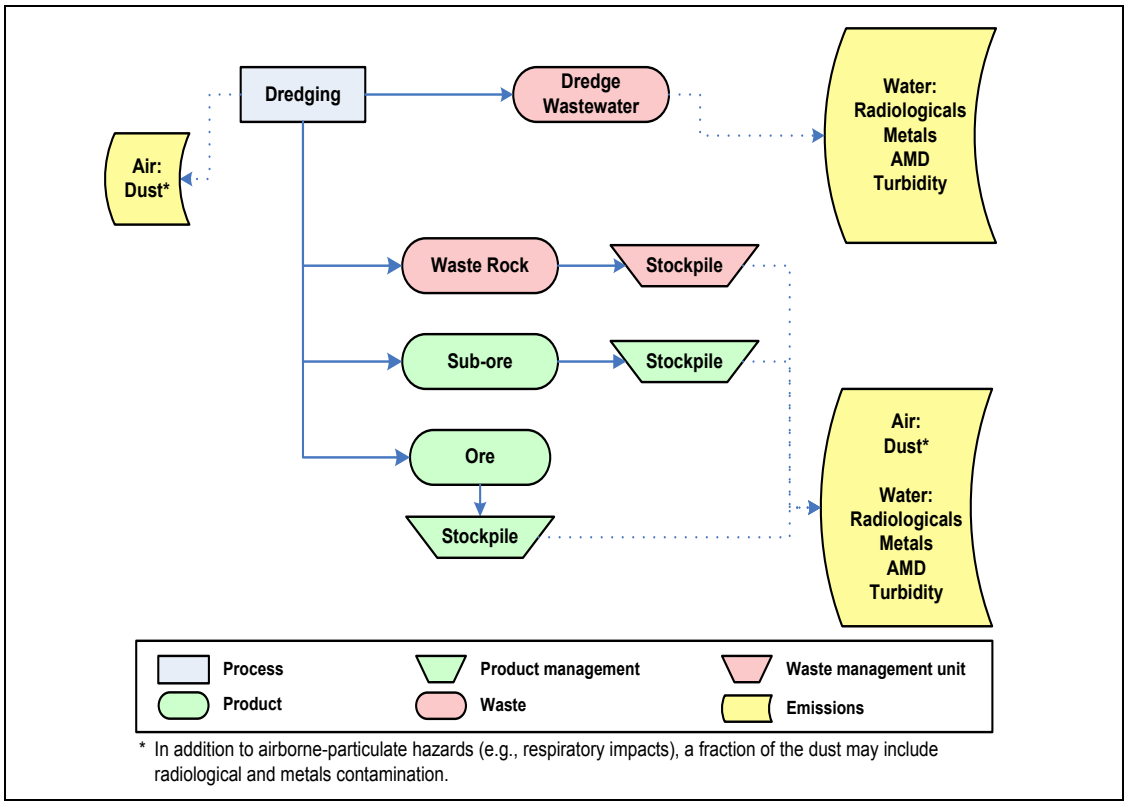

Figure 3-5. Conventional placer deposit processing and wastes emissions.

4. Resource Processing

Rare earth milling and processing is a complex, ore-specific operation that has potential for environmental contamination when not controlled and managed appropriately. Waste streams from REE processing have been identified, and their hazardous waste potential assessed. Although potentially significant, based on case studies and chemical composition, the waste streams with the greatest pollution potential are the tailings and their associated treatment and storage. Heavy metals and radionuclides associated with REE tailings pose the greatest threat to human health and the environment when not controlled. However, adoption of new technologies and management processes show potential to reduce the risk of environmental contamination.

The two major mineral sources of REEs are bastnasite and monazite and will be the focus of this section. However, it is important to note that production can come from a variety of minerals, such as xenotime, apatite, yttrofluorite, cerite, and gadolinite. Due to their strong affinity for oxygen, REEs are primarily present as oxidic compounds, and resources are often expressed as REOs. Processing REOs into usable products is a very complex process and often varies significantly between deposits. The major factors affecting the selection of treatment processes are listed below (Ferron et al., 1991):

- Type and nature of the deposit (e.g., beach sand, vein type, igneous and complex ores) and its complexity
- Type and nature of other valuable minerals present with REOs
- Type and nature of gangue minerals present in the deposit (e.g., slimes, clay, soluble gangue)
- Type and composition of the individual REO minerals
- The social and environmental acceptability of the process.

The primary steps involved in processing REOs are separation and concentration from the host material in acidic or alkaline solutions, separation of the REOs using solvent extraction or ion exchange, and reduction of the individual REOs into pure metals (Tran, 1991; Gupta and Krishnamurthy, 2004). The first step typically includes crushing the ore and separating the REO by flotation, magnetic, or gravimetric separation. This separation process dramatically increases the percentage of REOs in the working material. For example, the Mountain Pass mine separates and concentrates REOs in bastnasite from 7 percent to 60 percent. A tremendous amount of discarded waste rock (tailings) is generated in this process and is typically managed onsite or used as backfill material. Chemical changes typically do not occur during the first step, and this process is usually situated near the mine site to reduce transport costs.

Subsequent steps in the process aim to change the concentrated mineral into more valuable chemical forms through various thermal and chemical reactions. Typically utilizing hydrometallurgy techniques (e.g., leaching, extraction, precipitation), the mineral concentrates are separated into usable oxides. Further processing by techniques such as metallothermic reduction can refine the oxides or metal mixtures into high-purity REMs.

Figures 4-1 and 4-2 present block flow diagrams of typical extraction and processing steps involved in hardrock and placer mining operations that highlight potential environmental emissions.

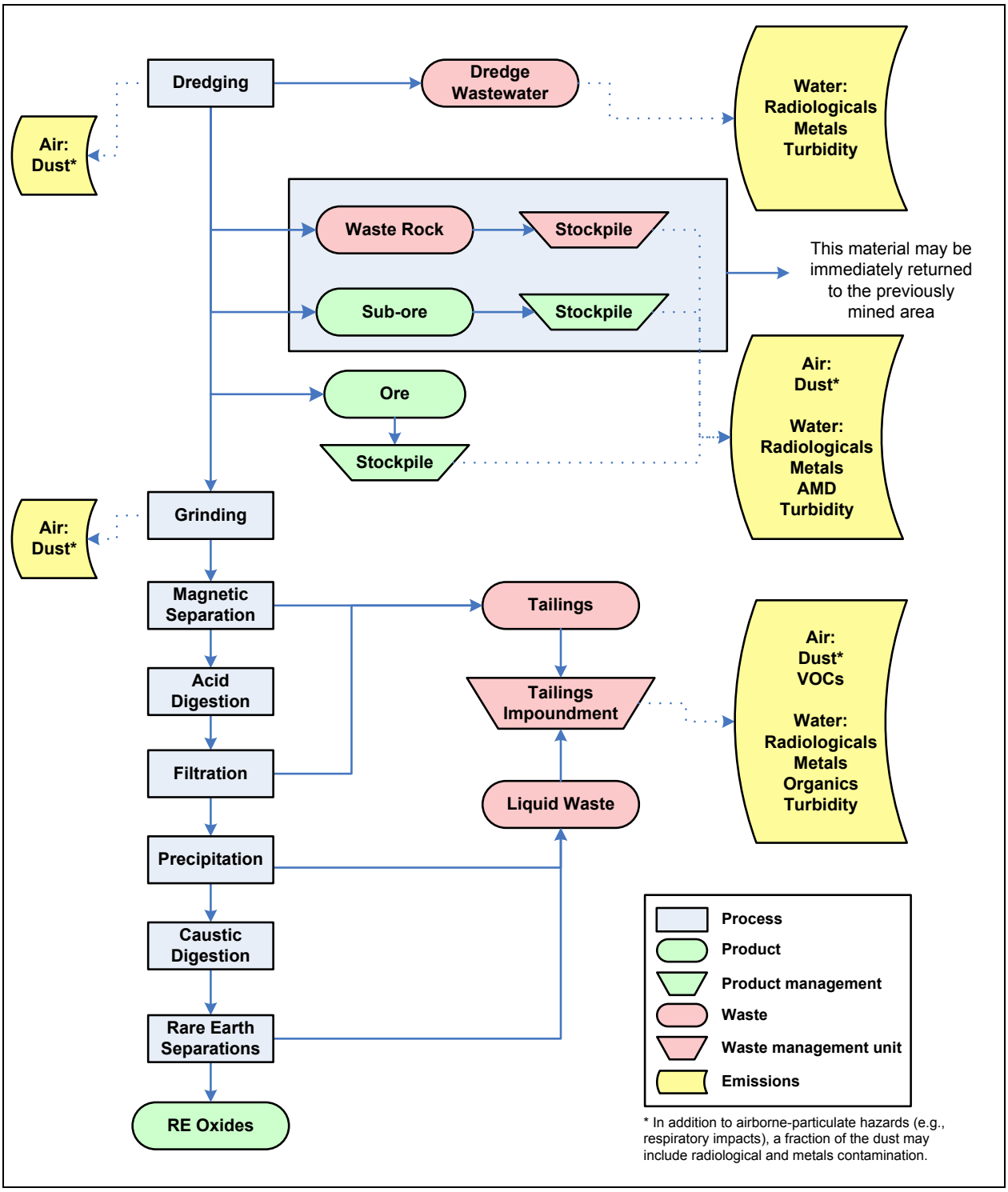

Figure 4-1. Conventional placer deposit resource processing and potential wastes emissions.

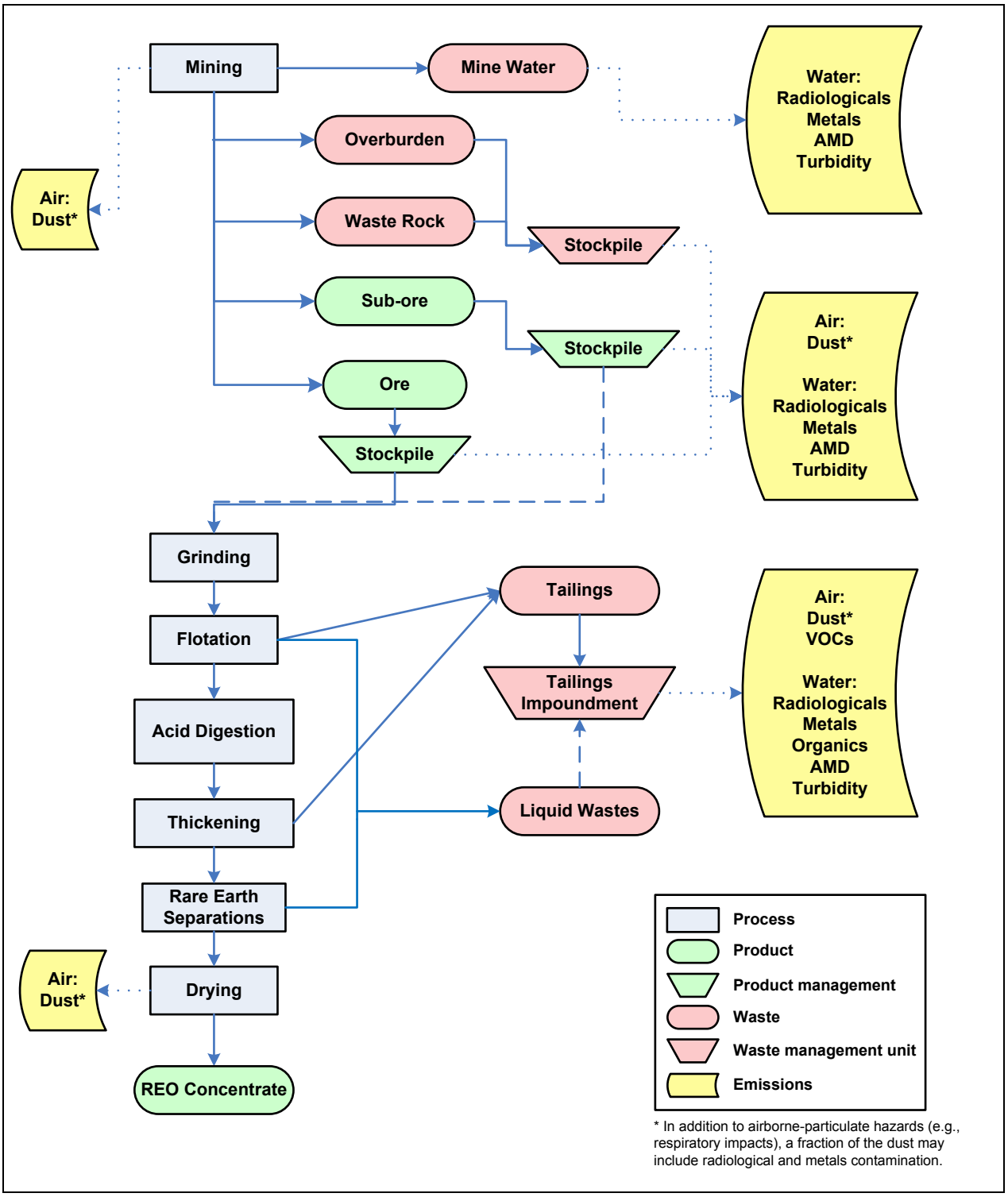

Figure 4-2. Conventional hardrock resource processing and potential wastes emissions.

4.1 Bevill Amendment

The 1980 amendment to the Resource Conservation and Recovery Act (RCRA), known as the Bevill exclusion, was enacted to exclude specific solid wastes from the extraction, beneficiation, and processing of ores and minerals. The EPA established criteria for determining beneficiation and process waste for each mineral production sector and reported this information in the final rule (54 Fed. Reg. 36592, 36616 codified at 261.4(b)(7)).

The EPA determined the line between beneficiation and processing of rare earths for one particular rare earth operation is when the ore is digested with concentrated acids or caustics (U.S. EPA, 1991). However, several factors are involved in making Bevill determinations, and official assistance should be sought from the RCRA authorized state or the EPA Regional office. The basic steps in making Bevill determinations are the following:

1. Determine whether the material is considered a solid waste under RCRA.
2. Determine whether the facility is using a primary ore or mineral to produce a final or intermediate product, and also whether less than 50 percent of the feedstock on an annual basis are from secondary sources.
3. Establish whether the material and the operation that generates it are uniquely associated with mineral production.
4. Determine where in the sequence of operations beneficiation ends and mineral processing begins.
5. If the material is a mineral processing waste, determine whether it is one of the 20 special wastes from mineral processing.

This process of determination will result in one of the three outcomes:

- The material is not a solid waste and therefore not subject to RCRA;
- The material is a solid waste, but is exempt from RCRA Subtitle C because of the Mining Waste Exclusion; or
- The material is a solid waste that is not exempt from RCRA Subtitle C and is subject to regulation as a hazardous waste if it is listed or characteristic hazardous waste.

The EPA offers online compliance assistance on the Bevill Amendment at the following Internet address: http://www.epa.gov/oecaerth/assistance/sectors/minerals/processing/bevillquestions.html.

4.2 Beneficiation Processes

As previously described in ***Section 4.1***, the beneficiation process does not alter the chemical composition of the ore; rather, these processes are intended to liberate the mineral ore from the host material. The crushing and grinding steps enable the exploitation of differences in physical properties such as gravimetric, magnetizability, and surface ionization potential to aid in separation (Aplan, 1988). The separation processes typically employed are (1) gravity separators, (2) electrical/magnetic separators, and (3) flotation separators.

Gravity concentration methods separate minerals of different specific gravity by exploiting the variance in their gravity-driven movement through a viscous fluid. For successful separation using this technique, there must exist a marked density difference between the mineral and the gangue. Examples of gravity separators include (1) jigs; (2) pinched sluices and cones; (3) spirals; (4) shaking tables; (5) pneumatic tables; (6) duplex concentrators; (7) Mozley laboratory separator; and (8) centrifugal concentrators.

Electrical and magnetic separation methods are considered similar because they exploit some of the same properties of the mineral and thus their application can overlap. Magnetic separators utilize the differences in magnetic properties between the mineral of interest and gangue. There are two primary classifications of materials when applying magnetic separation: (1) diamagnetic and (2) paramagnetic. Diamagnetic materials are repelled along the lines of magnetic force, while paramagnetic materials are attracted along the lines of magnetic force. There are two primary classes of magnetic separators: low- and high-intensity process units. Highly paramagnetic materials (e.g., ferro-magnetic) are typically separated using low-intensity separators, such as drum separators. Specifically for rare earths, roll separators that utilize alternate magnetic and non-magnetic laminations are commonly used. High-intensity separators are employed to separate very weak paramagnetic minerals and include common configurations such as induced roll magnetic separators and Jones separators. Electrical separation exploits electrical conductivity differences among various minerals in the ore. For optimum results, the ore feed needs to completely dry and only one particle deep. This restriction has limited the application primarily to beach and stream placers, such as those where REEs are found. Examples of electrical separators include plate and screen electrostatic separators.

In applications where the ore particle size is too small for efficient gravity separation, flotation is typically employed. Flotation exploits the hydrophobicity of the mineral of interest and the hydrophilicity of the gangue. Accordingly, the hydrophobic mineral particles tend to "stick" to the air bubbles that are delivered into the process unit and rise to the surface where they are separated. To aid in this process, a variety of chemicals are added to the ore slurry and include collectors, frothers, and modifiers.

4.2.1 Bastnasite Beneficiation

Although there are variations in the beneficiation of bastnasite, the general process involves crushing/grinding and separation by flotation. To provide a relevant example, details of the Molycorp Mountain Pass mine are presented. The ore containing bastnasite (7 percent REO) is crushed, ground, and classified in the milling process to achieve 100 percent passing a 150 mesh sieve prior to separation by hot froth flotation (Gupta and Krishnamurthy, 2004). Prior to flotation, the ore passes through six different conditioning treatments in which steam, soda ash, sodium fluosilicate, sodium lignosulfonate, and steam-distilled tall oil are added to aid the separation of the unwanted materials (often referred to as gangue). This process produces a 60 percent REO bastnasite concentrate. A detailed process flow diagram (PFD) of this process is presented in **Figure C-1** in ***Appendix C***.

4.2.2 Monazite/Xenotime Beneficiation

Typically associated with dredged mineral sands, the monazite or xenotime ore is separated and concentrated after course grinding via gravimetric, flotation, or magnetic processes. As expected, the complexity of this process is dependent on the specific reserve. A detailed PFD of a conventional monazite extraction and processing operation is presented in **Figure C-2** in ***Appendix C***.

4.3 Extraction Processes

Hydrometallurgy is the most common chemical extraction method of separating individual REOs from the mineral concentrate. Basicity differences between the various rare earths influence the solubility of their salts, the hydrolysis of ions, and the formation of complex species (Gupta and Krishnamurthy, 2004). The differences in these properties are exploited by fractional crystallization, fractional precipitation, ion exchange, and solvent extraction to separate the individual REOs. Although some of the individual REOs and rare earth chlorides resulting from these processes have market value, further processing and refining are required to produce high-quality pure metal end products to maximize value. These processes are also utilized to recover REEs from recycled materials. **Table 4-1** presents a list of rare earth extraction methods and a brief description of each.

Table 4-1. Rare earth extraction methods (adapted from Meyer and Bras, 2011)

Method	Type	Extraction Trait	Process
Liquid-Liquid Extraction	Hydrometallurgy	Solubility	The liquid containing the desired element is mixed with an immiscible solvent, which preferentially dissolves the desired element. When the liquids separate, the desired element separates with the solvent.
Solid-Liquid Extraction	Hydrometallurgy	Solubility	The solid is placed into a solvent, which dissolves the desired soluble component.
Solid Phase	Hydrometallurgy	Solubility	The fluid containing the desired element is poured through a sorbent bed, which forms equilibrium by the liquid adsorption to the solid surface or penetration of the outer layer of molecules on that source. Either undesired components can be washed-out or elutriants can be used to selectively extract the desired elements.
Ion Exchange	Hydrometallurgy	Chemical Affinity	The fluid containing the desired elements are mixed with an elutriant and poured through a resin. The molecules are separated based on their affinity split between the elutriant and the resin.
Super Critical Extraction	Hydrometallurgy	Variety	The fluid containing the desired element undergoes a reaction with CO_2 at or over the critical temperature of 31˚C and critical pressure of 72.9 atm. This amplifies minute differences between elements to allow separation.
Electrowinning	Electrometallurgy	Electronegativity	A current is passed from an inert anode through a liquid leach solution containing the metal. The metal is extracted by an electroplating process, which deposits the rare earths onto the cathode.
Electrorefining	Electrometallurgy	Electronegativity	The anode is composed of the recycled material. When the current passes from the anode to the cathode through the acidic electrolyte, the anode corrodes, releasing the rare earth solution into the solution, then electrowinning occurs.
Electro Slag Refining	Pyrometallurgy	Density	Electricity melts the metal. The molten metal is combined with a reactive flux, which causes the impurities to float off the molten metal into the slag.

4.3.1 Bastnasite Extraction

The desired end product(s) dictates the subsequent processing steps of the bastnasite concentrate. Typical processes include leaching, washing, filtering, and drying or calcining to increase the percent REO from approximately 60% up to as much as 90%. In previous operation, the Mountain Pass Mine produced three commercial grades of bastnasite, with end uses such as glass polishing powders and master alloys for iron and steel production. To produce individual lanthanides, the concentrate was first calcined to convert the contained cerium to plus four valency while leaving the other lanthanides in the plus 3 valency. Acid digestion followed and resulted in the dissolution of most of the non-cerium lanthanides. The resulting solution was then processed using multistage solvent extraction to produce high-purity rare earth compounds, such as (1) neodymium-praseodymium carbonate, (2) lanthanum hydrate, (3) cerium concentrate, (4) samarium oxide, (5) gadolinium oxide, (6) terbium oxide, and (7) europium oxide. A detailed PFD of this process in presented in **Figure C-1** in ***Appendix C.***

It is important to note that the Mountain Pass Mine (Molycorp Metals and Alloys) extraction processes and associated equipment are currently being upgraded and the previously described process may not accurately reflect planned or current practice.

4.3.2 Monazite/Xenotime Extraction

In one common method of processing monazite/xenotimes, the ore concentrate from the beneficiation process is first digested with 70 percent sodium hydroxide (NaOH), producing rare earth hydroxides. The rare earth hydroxides are then leached with HCl to recover the soluble rare earth chlorides. The rare earth chloride solution is then processed using multistage solvent extraction to produce individual, high-purity REOs (95–99.995 percent). A detailed PFD of this process is presented in **Figure C-3** in ***Appendix C***.

4.3.3 Tailings Extraction

Another potential source of REO is the tailings waste from other mineral processing operations. For example, the apatite tailings from the Pea Ridge iron ore mine and processing operation contain 0.5% REO. The two primary methods for extracting REO from apatite are selective acid extraction and physical separation techniques. Through gravimetric processes, the U.S. Bureau of Mines was able to recover 90% of the REO and produce a 70% lanthanide concentrate (US DOI, 1993). Specifically, the pulped apatite was mixed with oleic acid to collect the phosphate when pine oil was used as the frother. Three successive flotation steps yielded the desired lanthanides. The tailings impoundment currently contains 20 million tons that is over 7% apatite.

4.4 Reduction Processes

The liberation of REMs from compounds such as oxides or chlorides can be a very difficult process due to their extreme stability. Several methods have been developed to accomplish this task. However, the three primary methods of producing REMs are (1) reduction of anhydrous chlorides or fluorides, (2) reduction of REOs, and (3) fused salt electrolysis of rare earth chlorides or oxide-fluoride mixtures (Gupta and Krishnamurthy, 2004). Currently, only one facility is producing high-purity rare earth alloys and metals in the United States—the recent Molycorp acquisition, Santoku America, Inc., in Phoenix, AZ.

Metallothermic reduction (smelting) is the most widely used method for REM preparation. Reductants react in the furnace with oxidants (e.g., oxygen, sulfide, carbonate) to separate and free the metal.

Less common processes that can be employed in the reduction of rare earth compounds are

- Electrolysis
- Gaseous reduction
- Vacuum distillation
- Mercury amalgamate oxidation and reduction
- High-performance centrifugal partition chromatography
- Si-octyl phenyloxy acetic acid treatment.

4.5 Potential Environmental Impacts

The EPA (1991) previously identified specific waste streams in rare earth processing and assessed their hazardous waste potential (**Table 4-2**). The review identified four waste streams that would likely be classified hazardous: (1) waste solvent due to ignitability, (2) spent lead filter cake due to toxicity, (3) waste zinc contaminated with mercury due to toxicity, and (4) solvent extraction crud due to ignitability. However, the major environmental risk in mining and processing rare earths is associated with the treatment and disposal of the tailings (Oko-Institut e.V., 2011). The tailings typically contain high-surface-area particles, wastewater, and process chemicals. The impoundment areas are exposed to weathering conditions and have the potential to contaminate the air, soil, surface, and groundwater if not properly controlled and managed. Typical pollutants that have been associated with rare earth tailings

impoundments are solids; ore-associated metals (e.g., aluminum, arsenic, barium, beryllium, cadmium, copper, lead, manganese, zinc); radionuclides; radon; fluorides; sulfates; and trace organics. Fugitive dust from the tailings impoundment can contaminate the air and surrounding soil. Surface water runoff from precipitation events or dam overtopping can transport pollutants from the impoundment to surrounding soil and surface waterbodies. Additionally, if adequate groundwater protection measures are not utilized (e.g., impoundment liner), the potential exists to contaminate surrounding groundwater resources. A worst-case scenario is dam failure due to poor construction or from a catastrophic event, resulting in serious long-term environmental damage. However, proper design, operation, and management of a mine and its associated pollution control systems can greatly reduce the risk of environmental contamination from REE mining and processing activities.

Table 4-2. Rare Earth Processing Waste Streams and Their Hazardous Waste Potential (U.S. EPA, 1991)

Process Waste Stream	Hazardous Waste Potential
Off-gases from dehydration	None
Spent hydroxide cake	None
Spent monazite solids	None
Spent off-gases from electrolytic reduction	None (after appropriate treatment)
Spent sodium fluoride	None
Waste filtrate	None
Waste solvent	Ignitability
Spent lead filter cake	Toxicity
Lead backwash sludge	None
Waste zinc contaminated with mercury	Toxicity
Solvent extraction crud	Ignitability

*The process that generates waste zinc contaminated with mercury was generally abandoned in the 1990s.

4.5.1 China Legacy

China's high REE production, combined with limited environmental regulations, has resulted in significant environmental damage to the areas surrounding mining and processing operations. Operations range from large government-operated minTes and processing facilities to small illegal endeavors. Often, smaller operations have little or no environmental controls, and larger operations have only recently begun adopting such measures. For example, after 40 years of operation, the Bayan-Obo mine has an 11-km^2 tailings impoundment that has radioactively contaminated the soil, groundwater, and vegetation of the surrounding area (Oko-Institute e.V., 2011). As reported by Hurst (2010), The Chinese Society of Rare Earths stated that every ton of rare earth produced generates approximately 8.5 kg of fluorine and 13 kg of dust. Also, they reported the use of concentrated sulfuric acid during high-temperature calcinations produces 9,600 to 12,000 m^3 of waste gas containing dust concentrate, hydrofluoric acid, and sulfur dioxide, and approximately 75 m^3 of acidic wastewater, as well as 1 ton of radioactive waste residue (Hurst, 2010). Additionally, the REE separation and refining process known as saponification had been used extensively in China until recently, generating harmful wastewater. It was estimated that, in 2005, the process generated 20,000 to 25,000 tons of wastewater, with total ammonia nitrogen concentrations ranging between 300 mg/L and 5,000 mg/L (Oko-Institut e.V., 2011).

4.5.2 United States Legacy

The primary source of environmental contamination at the Molycorp Mountain Pass site was process wastewaters and tailings impoundments. Prior to 1980, the facility utilized onsite percolation-type surface impoundments to dispose of wastewater, while conventional dam impoundments were utilized to dispose

of tailings. These past operations have impacted groundwater at the site. The greatest impact has been an increase in total dissolved solids (TDS), primarily as a result of neutralizing HCl in the wastewater with sodium hydroxide (NaOH). Groundwater TDS concentrations impacted by unlined impoundments have been reported by the current operator in the range of 10,000 mg/L. Background concentrations of TDS have been documented by the current operator from 360 to 800 mg/L TDS, with low but detectable concentrations of barium, boron, strontium, and radiological constituents. Additional constituents such as metals, nutrients, and radiological constituents in the wastewater and tailings have potentially had a negative impact on groundwater quality. In 1980 and 1987, two additional off-site evaporation ponds were constructed to dispose of wastewater. During the time of operation of these units, multiple instances of mechanical failure of the pipeline connecting the Mountain Pass site to the evaporation ponds resulted in surface soil contamination. Specifically, two wastewater spills were documented at the site (U.S. EPA, 1994). The first spill, as reported by EPA, occurred in 1989 and involved the surface discharge of 3,375 gallons of tailings and process wastewater from a failed pipeline. The second spill occurred in 1990 and involved the surface discharge of 45,000 gallons of process wastewater from a failed pipeline. Both spills were contained onsite and deemed insignificant due to the low risk to human health and the environment.

Contaminated groundwater is actively being remediated. Groundwater interceptor wells and the mine pit have resulted in a cone of depression that is allowing capture and treatment of the contaminated plumes (CA RWQB, 2010). Additionally, the pipeline involved in the wastewater spills is currently being removed by the former mine owner.

The newly proposed facility will utilize multiple technologies and management strategies to minimize environmental impacts. The primary improvement involves the management of water and tailings. Dewatered tailings result in a "paste'" that is pumped to an onsite location and layered into a stable containment mound. The process will result in the elimination of 120 acres of evaporation ponds. Reverse osmosis (RO) will be used to treat and reuse 90 percent of the wastewater, while the RO reject will be further treated to produce value-added products that can be reused in the process or sold. An onsite chlor-alkali facility will use the treated RO reject from the previous step as feed to produce NaOH, HCl, and sodium hypochlorite (NaClO) for reuse or for sale (RTI International, 2011). However, as with any reuse technology, the result is often a concentrated wastewater stream that will require disposal. In the Molycorp-proposed process, pollutants such as heavy metals concentrated in the RO reject are destined for precipitation and removal via nanofiltration. The brine from this process will be dried in on-site evaporation ponds prior to final disposal. Based on available information, **Figure 4-3** presents a simplified block flow diagram of the proposed wastewater and tailings treatment process that highlights potential environmental emission points and potential contaminants of concern. It is reported that this approach would also result in less chemical use, less water consumption, and reduced reagent trucking volume (RTI International, 2011).

Additional improvements and management strategies include (1) improved milling to improve resource recovery and lessen tailings volume per unit of REO produced, and (2) utilization of a new natural gas pipeline to supply a combined heat and power system to provide electricity and heat that is 20 percent more efficient than the previous methods (RTI International, 2011).

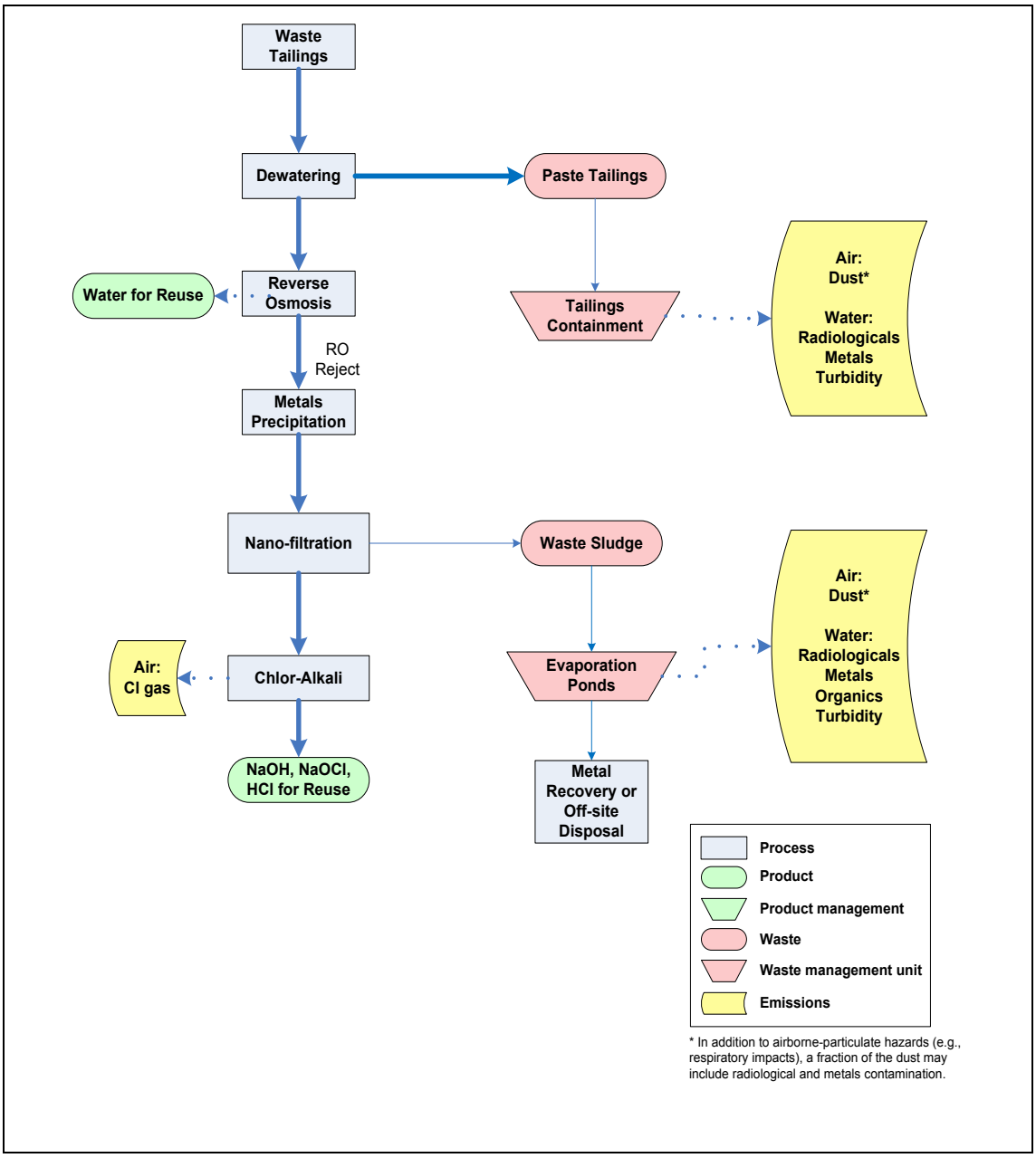

Figure 4-3. Anticipated Molycorp Mountain Pass mine water reclamation process and potential waste emissions.

5. Rare Earth Element Recovery/Alternative Material Use

Increased demand and reduced supply of REEs, along with the knowledge of the quantities available in waste products, has resulted in expanded research and development efforts focused on the recycling of rare earths. Currently, commercial recycling of rare earths is very limited; however, it is reported in the literature that, within the next year, several new commercial recycling operations will begin operation, with the focus being on magnets, batteries, lighting and luminescence, and catalysts. Recycling of postconsumer, end-of-life products, typically involves four key steps: (1) collection; (2) dismantling; (3) separation (preprocessing); and (4) processing. A general description of each step is provided, along with the potential waste streams and environmental impacts. While environmental impacts can occur, when compared with primary processing, it is reported that controlled recycling of REEs will provide significant benefits with respect to air emissions, groundwater protection, acidification, eutrophication, and climate protection.

5.1 Introduction

While research on methods for recycling and recovering REEs from as early as 1984 was identified during our literature review, it is not until recently that more attention within industry and the literature has been given to the topic of REE recycling. The primary drivers for this renewed focus include the increased demand for REEs, concern about REE supplies, increasing cost of REEs, and new policies implemented by some countries mandating REE recycling for selected items. For example,

- Annual global production of REEs totals about 124,000 tons, according to a July 2010 report by the U.S. Congressional Research Service. By 2014, global demand could exceed 200,000 tons per year, which would exceed current production by over 75,000 tons per year, according to the report (Humphries, 2010);
- Currently, China produces over 95 percent of all REEs used in the world. This monopoly has resulted in concerns with respect to supplies and prices of REEs; and
- Prices are increasing rapidly for REEs and REOs. Dysprosium, which sold for $300/kg in 2010, is selling for $3,600/kg in 2011 (Gordon, 2011). **Figure 5-1** illustrates price trends for selected REOs over the past few years.

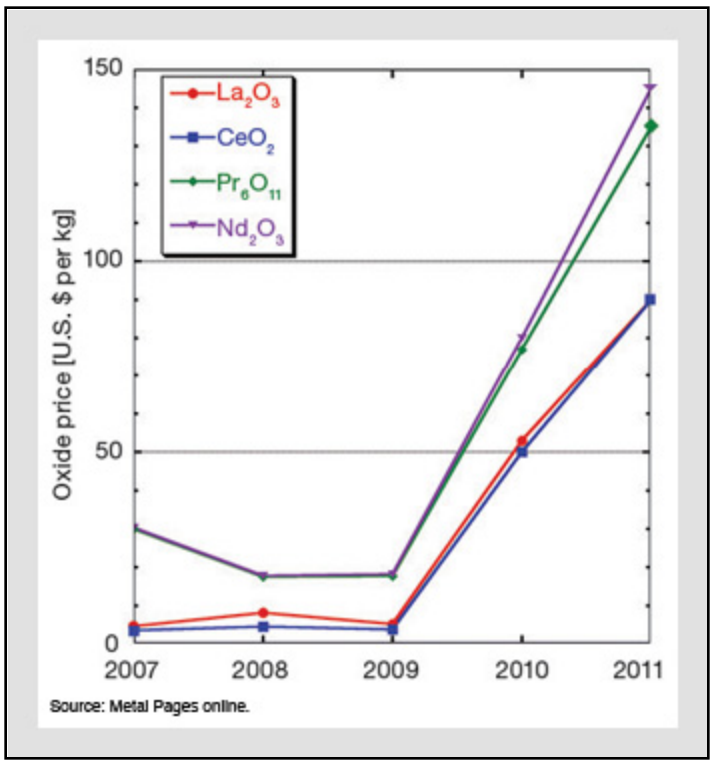

Figure 5-1. Representative rare earth oxide prices from 2007–2010 (The 2007–2010 figures are fourth-quarter [Q4] average prices. The 2011 numbers represent spot prices on February 25).
(from: http://www.osa-opn.org/OpenContent/Features/Rare-Earth-Elements-High-Demand-Uncertain-Supply-3.aspx)

Information from the literature indicates that large amounts of REEs are currently in use or available in waste products and would be able to support recycling operations. Specifically, a recent study by the Japanese government-affiliated research group National Institute for Material Science (NIMS) estimated that Japan has 300,000 tons of REEs and 6,800 tons of gold currently sitting in e-wastes (Tabuki, 2010). A recent study by Yale University estimated that 485,000 tons of REEs were in use globally in 2007 (Du and Graedel, 2011). The study further states that four REEs (cerium, lanthanum, neodymium, and yttrium) constituted more than 85 percent of the global production, and that recycling the in-use stock for each of these is possible, but remains a challenge. The research concludes that for the other rare earths that are generally used in much lower quantities, recycling would be difficult primarily due to technical challenges associated with separating the rare earths from the product. On an individual basis, cerium is mostly concentrated in catalytic converters and metal alloys; neodymium is used in permanent magnets, computers, audio systems, cars, and wind turbines; lanthanum is used in catalysts, metal alloys, and batteries; and yttrium is used in lasers and superconductors. A newly published report by the USGS provides additional information on the end uses of REEs and the potential for recyclability by end use (Goonan, 2011).

To put use quantities in perspective, a Toyota Prius uses 2.2 pounds of neodymium (Wheeland, 2010) and over 10 pounds of lanthanum (Koerth-Baker, 2010); a typical air conditioner unit includes 4 magnets that contain about 30 grams of rare earths (Montgomery, 2011); and a new-generation windmill requires 1,500 pounds of neodymium (REVE, 2011).

A recent United Nations (UN) report on recycling rates of metals estimates that the end-of-life functional recycling (i.e., recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use) for rare earths is less than 1 percent (UNEP, 2011). Another study estimates that world-wide, only 10 percent to 15 percent of personal electronics are being properly recycled (Dillow, 2011). Of the items that are sent for recycling, the European Union (EU) estimates that 50 percent of the total is illegally exported, potentially ending up in unregulated recycling operations in Africa or Asia. These recycling operations frequently result in environmental damage and worker exposure, as documented in a separate UNEP report (Schluep et al., 2009) and discussed further in ***Section 6***.

> "If the United States committed itself to meeting its critical materials needs in large part through recycling, there is no nation on earth that could match American resources. The United States has the largest "above-ground" mines of critical materials in the world, in the sense that this country's supply of industrial scrap and end-of-life automobiles, electronics, and electronic appliances - whether they are in wreckers' yards, land-fills, or Americans' basements and attics - can't be matched by any other nation. In essence, these "above-ground mines" make the United States the Saudi Arabia of critical materials. A well-developed recycling system could tap these mines for U.S. critical materials security without limit."
>
> **Waste Management World, 2011**

The increasing prices of REEs (as well as other recyclable metals), along with the knowledge of the quantities available in discards and the increased worldwide demand, have led to the concept of "urban mining." Urban mining is defined as the recovery of elements and compounds from waste materials and products. Consumer electronics are increasingly becoming subject to urban mining practices—and with over 6.5 million metric tons of personal computers, computer monitors and peripherals, televisions, and mobile devices being generated in 2007 in the United States, Europe, China, and India—the supply available for "mining," or recycling, is large and increasing (ICF International, 2011). A short introductory video on urban mining, with a focus on efforts in Japan, is available on the Internet (http://english.ntdtv.com/ntdtv_en/ns_offbeat/2010-10-19/822469802087.html).

Some small electronics such as cell phones reach their end of life after a few years, while many of the products that contain larger amounts of REEs have useful lives of well over one decade. The recycling of the REEs contained within products will occur many years in the future and is not a short-term solution to the current demand. Another factor that will impact one of the recycling drivers is that as additional REE mines begin operation outside of China, global production will increase, costs may decrease, and the urgency behind the push to recycle may be reduced.

5.2 Recycle Processing Steps

The recycling process for post-consumer, end-of-life products typically involves four key steps, as illustrated by **Figure 5-1**: (1) collection; (2) dismantling; (3) separation (preprocessing); and (4) processing.

As previously noted, a 2011 status report (UNEP, 2011) states that the end-of-life recycling rates, defined as the "percentage of a metal in discards that is actually recycled," for REEs is less than 1 percent. As cited by Meyer and Bras (2011), the consumer products with the most rare earth recycling potential are the ones that contain high levels of rare earths and an established collection or recycling infrastructure, such as fluorescent lamps, magnets, car batteries, and catalytic converters. Three factors noted as contributing to the effectives of recycling efforts are the following (UNEP, 2011):

1. **Economics** – The value of the materials to be recycled must be greater than the cost of recycling. In situations where this is not the case, laws and incentives can be effective in increasing recycling rates.

2. **Technology** – Products that are designed with recycling in mind will be easier to disassemble and re-process.
3. **Societal** – Programs will be more effective when the public is aware of the benefits of recycling and the collection and recycling infrastructure is accessible and well publicized.

Recycling can be conducted on either pre-consumer or post-consumer items. While most of the literature identified pertains to post-consumer recycling initiatives, it has been reported that 20 to 30 percent of rare earth magnets are scrapped during the manufacturing process and that research is ongoing to develop ways for recycling this "waste stream" (Schuler et al., 2011). Similar information was not identified for other pre-consumer items, but may prove to be an opportunity in the future for manufacturing processes with high scrap rates.

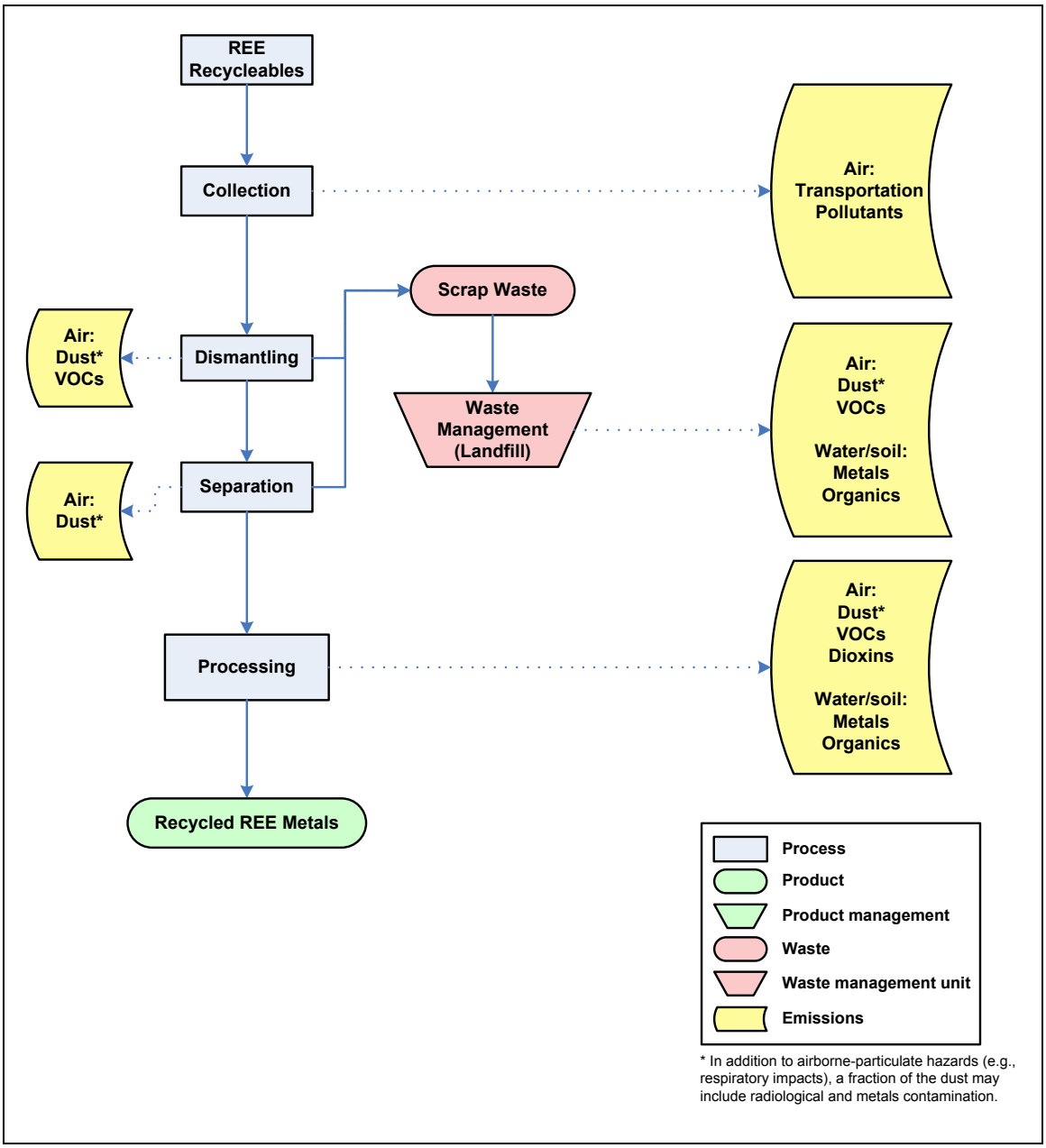

Figure 5-2. REE recycling steps and waste emissions.

5.2.1 Collection

The first step, defined as collection, is discussed in the recent report by UNEP (Schluep et al., 2009) and can be accomplished through a variety of means, but it is generally more efficient when a collection infrastructure is already established. In the past, state regulations have been effective at establishing the collection and recycling infrastructure required to increase recycling rates for consumer goods in the United States. For example, in the 1980s, the recycling of lead-acid car batteries became required by many states and resulted in a 95 percent recycling rate by 1990. The EPA data show that, nationally, 19% of consumer electronics were recycled in 2009 (Bomgardner, 2011). As of May 2011, 25 states have laws requiring e-waste recycling, and 5 additional states have pending laws. In most cases, manufactures are required to cover the costs associated with the collection and recycling. A summary of these state laws and information on collection volumes to date is available on the Internet (Electronic Take Back Coalition, 2011). In further support of electronics recycling, the Responsible Electronics Recycling Act was introduced into the U.S. House of Representatives in June 2011(H.R. 2284) and includes as one of three main focus areas: support for collection, logistics, and supply chain optimization to support REE recycling.

The EPA's Plug-In To eCycling Partners website provides links to take-back programs and drop-off locations for mobile devices, computers, printers, and televisions. The partners include retail stores, equipment manufacturers, and mobile device service providers. Together, they collected and recycled 68 million pounds of used consumer electronics in 2008 (U.S. EPA, 2008b). Collection methods include direct mail of products to locations established by equipment manufactures and drop off of used products at designated locations, such as retail stores or locations specifically setup as part of collection day events. Environmental impacts from the collection step are most predominantly due to transportation/shipping of materials to the collection point and from the point of collection to the location of the processing facility.

5.2.2 Dismantling/Preprocessing

Dismantling and preprocessing steps are critical for separating the high-value components from less valuable materials. Frequently, high-value materials such as REEs and other metals, like gold, make up a small percentage of the item being recycled, and separation steps will make it more efficient to recover them. However, even when metals are separated from other nonmetal components, mixed metal scrap is more challenging to recycle than segregated metals.

Typical dismantling and preprocessing steps include manual or mechanical separations, manual or mechanical disassembly, mechanical shredding, and screening. The specific details of each step are reported in the literature and are dependent on the item being recycled and the material being recovered (Schluep et al., 2009). **Figure 5-2** provides photos of a facility where computer hard disk drives are manually disassembled, and of the resulting separated components, including magnets containing REEs.

Figure 5-3. Left: Dismantling table with pneumatic tools used for manual dismantling of hard disks. Right: Components resulting from the process and including REE-containing magnets (upper right corner) (Schluep et al., 2009).

Advances to manual separation methods are being investigated as a way to reduce costs, increase speed, and reduce potential worker exposures. Two examples of successes in this area are the following:

- A process developed by Hitachi for disassembling hard disk drives that involves placing the drives in a rotating drum where forces such as shock and vibration are employed. This process is reported to be eight times faster than manual separation and, therefore, more cost-effective (Clengfield et al., 2010).
- A process developed by NIMS that includes a small-scale electronic crushing device that, in a few seconds, is able to reduce cell phones and small home appliances to small pieces. This step is followed by placing the pieces in a three-dimensional ball mill that degrades the parts recovered from the crushing device to a powdered form. Because of the short treatment time in the ball mill, the remaining pieces of plastics and other materials remain intact and therefore can be recovered in a condition that allows for plastic recycling. The powder can then be further processed to recover metals of concern (NIMS, 2009).

During the dismantling and preprocessing steps, hazardous or other unwanted substances have to be removed and then either stored or treated safely while valuable materials are removed for reuse or recycling. For devices containing ozone-depleting substances, such as refrigerators and air-conditioners, the degassing step is crucial in the preprocessing stage because the refrigerants used (e.g. chlorofluorocarbon or hydrochlorofluorocarbon, in older models) need to be removed carefully to avoid air emissions of ozone-depleting substances, which have a large global warming potential. LCD monitors containing mercury or other toxic metals need to be dismantled with care to ensure worker and environmental protection. Circuit boards present in electronic equipment can contain lead in solder and flame retardants containing resins (Schluep et al., 2009). After removal of the hazardous and other special components, the remainder of the item being recycled can be further separated by manual dismantling or mechanical shredding and (automated) sorting techniques. Some shredding technologies have the potential to generate dust or other particulate matter that can impact worker health. Additionally, all mechanical processing equipment requires energy inputs that have additional associated environmental impacts.

5.2.3 Processing

After completion of the preprocessing steps, the components of interest are ready for the processing step. Processing technologies that are currently used, or are in the research stage, for the recovery of REEs are discussed in several references (Schuler et al, 2011; Ellis et al., 1994; Schluep et al., 2009; ICF International, 2011; Meyer and Bras, 2011) and can be grouped into the following general categories:

- Pyrometallurgy processes are energy intensive, using high temperatures to chemically convert feed materials and separate them so that the valuable metals can be recovered. It should be noted that rare earths can oxidize easily in these types of processes, making recovery difficult. While one recycling facility in Japan reportedly is recovering REEs using this type of process (Tabuki, 2010), others companies such as Umicore and Alcoa are conducting research that will enable wider use of this type of technology for REE recycling. During smelting, volatile organic compounds (VOCs) and dioxins could be generated and would need to be managed.
- Hydrometallurgy processes use strong acidic or basic solutions to selectively dissolve and then precipitate metals of interest from a preprocessed powder form. The specific process used will vary depending on the metal to be recovered, but options could include solvent extraction, leaching, and selective precipitation, among others. Variations of this type of technology are frequently reported in the literature, and a recent summary is provided by Schuler et al. (2011). The fundamental processes used for recycling REEs are the same as those utilized for raw ore. Accordingly, the waste streams and pollutants of concern are the same as those presented in ***Section 4***. In short, chemical and particulate air emissions, as well as slag material from the smelting process are all potential pollutant sources.
- Electrometallurgy processes such as electrowinning (where a current is passed from an inert anode through a liquid leach solution containing the metal; the metal is extracted by an electroplating process, which deposits the rare earths onto the cathode), and electrorefining (where the anode is composed of the recycled material--when the current passes from the anode to the cathode through the acidic electrolyte, the anode corrodes, releasing the rare earth ions into the solution, then electrowinning occurs). No specific information was located on environmental impacts from these processes when they are used to recycle REEs; however, they are expected to be similar to those identified in Section 4 for primary processing operations.
- Dry processes (research stage) use hydrogen gas at atmospheric pressure to turn neodymium-containing magnets to a powder that can then be re-formed into new magnets under heat and pressure. This research is being conducted at the University of Birmingham in the United Kingdom, and while the newly produced magnets are not of the same quality as the originals, they are suitable for use in motors (Davies, 2011).
- Tailings recycling involves reprocessing of existing tailings to recover the remaining amounts of REEs they contain. Recycling of tailings generally will occur at the same location as the mining operation using existing processes and equipment and resulting in the same contaminants as when processing the original ore. As reported by Xiaozhi (2011), the economic benefit, energy savings, and environmental benefits can be significant.
- Microbe-filled capsule technology (research stage) has been recently reported in the literature as being developed jointly by Morishita Jintan Co. and Osaka Prefecture University. With this technology, capsules are reportedly placed in a medium containing rare metals, and the microbes then absorb the metals. While the research to date has focused on rare metals (not specifically rare earths), it is thought to be transferable. If this is in fact proven to be true, an official at the Japan Society of Newer Metals has indicated that it could help to make REE recycling more cost-effective (Alibaba.com, 2010).
- Titanium dioxide process (research stage): While evaluating a process to develop methods for extracting higher yields of titanium dioxide, researchers from the University of Leeds, Faculty of

Engineering discovered how to recover significant quantities of REOs present in titanium dioxide mineral. While the original benefits of this technology were thought to be that it could improve purity, eliminate hazardous wastes, and cut costs and CO_2 emissions, the team also discovered that they could extract significant quantities of REM oxides as co-products of the refining process. Current recovery rates of oxides of neodymium, cerium, and lanthanum vary between 60 percent and 80 percent and are thought to be able to be increased in the future (University of Leeds, 2009).

5.3 Commercial REE-Recycling Applications

Review of the literature indicates that the number of commercial REE-recycling operations is limited, but that is likely to change in the near future due to the number of operations under development and the amount of research that is ongoing. **Table 5-1** provides a summary of commercial, or soon-to-be-commercial, operations by selected companies and includes the information that is known on the target item to be recycled, the materials being recovered, the technology to be used, the anticipated time frame until commercial application; notes with respect to cost or environmental benefits; and the source of information. Consistent with the information reported here, the literature indicates that the focus of REE-recycling research and commercialization efforts has been on magnets, batteries, lighting and luminescence, and catalysts (Schuler et al., 2011). It should be noted that in many cases, the companies that are in the process of developing or deploying recycling technologies have not published reports or papers with the details of their individual processes, as these are generally a competitive advantage and considered proprietary.

Table 5-1. Recycling Operations, Technologies Utilized, Current Status, and Benefits

Company	Target Feedstock/ Element	Technology to Be Used	Anticipated Time to Commercialization	Benefits (Cost and Environmental)	Source
Hitachi	Rare earth magnets from air conditioner compressors and hard disk drives	Automated separation process and dry extraction process	Anticipates recycling will meet 10% of its need by 2013 when facility goes online	Dry extraction method that allows processing without acids; resulting waste water problem. Automated separation process is faster than manual. Cost savings anticipated.	http://www.hitachi.com/New/cnews/101206.pdf
Toyota	Hybrid car batteries	Unknown	Ongoing	Main driver is supply concerns	http://shanghaiscrap.com/?p=5654
Japan's Shin-Etsu Chemical	Air conditioners	Plans to recycle recovered REEs into magnets	2011	No information readily available.	http://www.mattternetwork.com/2011/3/new-push-recycle-rare-earth.cfm
Showa Denko KK	Dysprosium and didymium (a mixture of praseodymium and neodymium)	No information readily available.	Estimated output of 800 tons from recycling facility	No information readily available.	http://www.bloomberg.com/news/2010-12-08/hitachi-recycles-rare-earth-as-china-crimps-supply.html

Company	Target Feedstock/ Element	Technology to Be Used	Anticipated Time to Commercialization	Benefits (Cost and Environmental)	Source
Mitsubishi (with Panasonic and Sharp)	Neodymium and dysposium, washing machines and air conditioners	No information readily available.	Currently in research stage. Anticipated production stage by 2014	No information readily available.	http://www.bloomberg.com/news/2010-12-08/hitachi-recycles-rare-earth-as-china-crimps-supply.html
Kosaka, Dowa Holdings	Existing electronics recycling plant—future processing of neodymium.	Smelter—300 tons of material per day are processed, resulting in 150 grams of rare metals	Research being conducted to develop technologies for REE recovery	Factory is making money. Process for neodymium extraction is estimated to be costly.	http://www.nytimes.com/2010/10/05/business/global/05recycle.html?emc=eta1
Raptor Technology Group	Mine tailings (from hardrock ore deposits from Washoe mine).	"Advanced chromatog-raphy and innovative separation technologies"	2,000 tons of ore per year, currently. New facility being built with capacity of over 10,000 tons of ore per year.	Cost savings; reclaimed mine wastes; chemical recycling and water savings.	http://www.raptortechnologygroup.com/general.php_category=Raptor+Technologies=metal.php
Creative Recycling Systems/ GreenRock Rare Earth Recovery Corporation	Electronics	"Closed loop" process. Details not available	By end of 2011, estimated to have four processing facilities with a capacity to process 500 million pounds of electronics per year.	No information readily available.	http://www.sustainablebusiness.com/index.cfm/go/news.display/id/21900
Wings Enterprises Inc.	Tailings from previous mining at Pea Ridge, Missouri	No information readily available.	Within 12 months.	No information readily available.	http://www.raremetalblog.com/2011/01/rare-earths-producer-molycorp-rivals-seek-us-aid-as-china-chops-exports.html
Umicore and Rhodia	Nickel Metal Hydride (NiMH) rechargeable batteries	Umicore's proprietary Ultra High Temperature (UHT) battery recycling process in combination with Rhodia's rare earth refining processes	First production expected by end of 2011.	This is the first known technology for recycling rare earths from NiMH batteries. "A typical NiMH battery will contain some 7% of rare earth elements including cerium, lanthanum, neodymium and praseodymium. This equates to 1 gram of rare earth for a AAA battery, 60 gram for a household power tool and 2 kilograms for a hybrid electric vehicle battery."	http://www.euronext.com/fic/000/064/994/649944.pdf

5.4 Environmental Implications of Recycling REEs

As recently reported by UNEP (Schluep et al., 2009), uncontrolled recycling of e-wastes has the potential to generate significant hazardous emissions. While this report is focused on e-wastes, the emission categories presented below pertain to the recycling of other types of wastes as well:

1. **Primary emissions** – Hazardous substances contained in e-waste (e.g., lead, mercury, arsenic, polychlorinated biphenyls [PCBs], ozone-depleting substances).
2. **Secondary emissions** – Hazardous reaction products that result from improper treatment (e.g., dioxins or furans formed by incineration/inappropriate smelting of plastics with halogenated flame retardants).
3. **Tertiary emissions** – Hazardous substances or reagents that are used during recycling (e.g., cyanide or other leaching agents) and are released because of inappropriate handling and treatment. Again, as reported by UNEP (Schluep et al., 2009), this is the biggest challenge in developing countries engaged in small-scale and uncontrolled recycling operations.

For recycling operations using pyrometallurgy, facilities need to have regulated gas treatment technologies installed and properly operating to control VOCs, dioxins, and other emissions that can form during processing.

In hydrometallurgical plants, special treatment requirements are necessary for the liquid and solid effluent streams to ensure environmentally sound operations and to prevent tertiary emissions of hazardous substances.

Recovering metals from state-of-the art recycling processes is reported as being 2 to 10 times more energy efficient than smelting metals from ores. Recycling also generates only a fraction of the CO_2 emissions and has significant benefits compared to mining in terms of land use and hazardous emissions. While examples are not provided in the literature specifically for REEs, production of 1 kg aluminum by recycling uses only one-tenth or less of the energy required for primary production and prevents the creation of 1.3 kg of bauxite residue, 2 kg of CO_2 emissions, and 0.011 kg of SO_2 emissions. For precious metals, the specific emissions saved by state-of-the-art recycling are reported as being even higher (Schluep et al., 2009).

Schuler et al. (2011) report that when compared with primary processing, recycling of REEs will provide significant benefits with respect to air emissions, groundwater protection, acidification, eutrophication, and climate protection. This report also states that the recycling of REEs will not involve radioactive impurities, as is the case with primary production.

Additional benefits of recycling that are not directly linked with the environment include improved supply of REEs, and therefore less dependence on foreign sources; the potential for reduction in REE costs due to supply increases and reduction of the current "monopoly" from foreign suppliers; and the potential for job creation from an expanded recycling industry.

5.5 Research on Alternatives to REEs

Research into alternative materials is another strategy that is being explored in response to the REE supply issues. Generally, this can fall into two main categories: research into alternatives to REEs, or research into alternative product designs that require fewer or no REEs. Schuler et al. (2011) provides an analysis and summary of the substitutes. This reference, along with many others, stresses the need for additional research in this area. As reported in March 2010 by *Science* magazine (Service, 2010), examples of selected research efforts under way include the following:

- IBM researchers have developed alternatives to the indium-containing films used in solar cells. The alternatives have included elements such as copper, zinc, tin, and sulfur—all of which are currently plentiful and relatively inexpensive. While performance is still lacking, it is getting close to that required for commercialization.
- University of California, Los Angeles, researchers are working on replacements for indium used in transparent conductors in electronic displays. The alternatives that they have developed include single-atom-thick sheets of carbon and carbon nanotubes.
- Researchers at the University of Delaware, Newark, have received funding to develop high-strength magnetic material from neodymium, iron, and boron nanoparticles. While still requiring some neodymium, their process is thought to be able to yield as much magnetization using smaller amounts of rare earths.
- Japanese researchers have been studying iron nitride as a candidate magnet material that does not use any REEs as part of the Rare Metal Substitute Materials Development Project, led by Japan's New Energy and Industrial Technology Development Organization (NEDO) (http://techon.nikkeibp.co.jp/english/NEWS_EN/20110307/190128/).
- NEDO is in the process of developing a motor for hybrid vehicles that uses ferrite magnets rather than REE-containing magnets (Tabuki, 2010). According to a report by the Associated Press Toyota is also working on a new type of motor which does not use any REMs. This could dramatically reduce production costs and, therefore, the cost of electric vehicles (Gordon-Bloomfield, 2011).
- Researchers at Ames Laboratory (a U.S. DOE laboratory) are evaluating methods for making neodymium-iron-boron magnets less expensively and without generating the hazardous by-products formed by today's standard manufacturing methods. Other researchers at Ames Laboratory are searching for substitutes to permanent magnets that will not require REEs. Focus areas include the Alnico iron-alloy family, iron-cobalt-based alloys, and nanostructured compounds made from combinations of REEs and transition metals (Jacoby and Jiang, 2010). Also, in June 2011, Ames Laboratory announced a new partnership with the Korean Institute of Industrial Technology. The objectives of this partnership are to: improve processing techniques for rare earths, transfer rare earth discoveries to industrial applications, and educate scientists and engineers on rare earths (U.S. DOE, 2011a).
- GE Global Research, in Niskayuna, New York, has recently received a $2.25 million grant from DOE for a project titled "Transformational Nanostructured Permanent Magnets." The objective of this grant is to "develop next-generation permanent magnets that include lower content of critical rare-earth materials." The focus of the effort will be to develop bulk nanostructured magnetic materials, resulting in a "dramatic increase in performance over state-of-the-art magnets" (Terra-Magnetica, 2010).

5.6 Emerging Policies/Programs to Support REE Recycling

REE recycling and research are dynamic fields, with new information becoming available almost daily. In conjunction with that, there are rapidly developing government policies and research initiatives aimed at ensuring continuing supply of REEs. At the time of this report for example in the United States, the Rare Earths Supply-Chain Technology and Resources Transformation Act of 2010 (H.R. 4866, or RESTART Act) had recently been introduced to Congress. The objective of this bill is to re-establish a competitive domestic rare earth minerals production industry; a domestic rare earth processing, refining, purification, and metals production industry; a domestic REMs alloying industry; and a domestic rare earth–based magnet production industry and supply chain in the United States. Selected other U.S. and international activities follow:

- In April 2011, DOE announced that through the ARPA-E program it would be providing up to $30 million in funding for a new research area called Rare Earth Alternatives in Critical Technologies (REACT). The goal will be to fund early-stage technology alternatives that reduce or eliminate the dependence on rare earth materials by developing substitutes for REEs used in electric vehicle motors and wind generators.
- The Responsible Electronics Recycling Act was introduced into the U.S. House of Representatives in June 2011(H.R. 2284) and would add a section to the 1976 Resource Conservation and Recovery Act (RCRA). The purpose of this Act would be to prohibit U.S. companies from exporting certain electronic wastes to developing countries. Associated with this Act will be the establishment of a Rare Earth Materials Recycling Research Initiative that will fund projects in three main areas: (1) removal, separation, and recycling of rare earth metals from electronics; (2) new electronics design that promotes ease of separation and recycling; and (3) collection, logistics and supply chain optimization to support REE recycling.
- The Critical Minerals Policy Act (S. 1113) was introduced to the U.S. Senate in May 2011 and is intended to modernize U.S. policies related to production, processing, manufacturing, recycling and environmental protection. The Act is focused on minerals identified as being most critical to military security and a strong economy (Lasley, 2011).
- The proposed Critical Minerals and Materials Promotion Act of 2011 (S. 383) directs the U.S. Department of Interior to conduct research related to ensuring the supply of critical minerals throughout the supply chain.
- The Center for Resource Recovery and Recycling (CR^3), funded by the National Science Foundation and industry partners, was established in 2010 and is located at the Colorado School of Mines, Worchester Polytechnic Institute, and the Katholieke Universiteit Leuven in Belgium (Worcester Polytechnic Institute, 2011). As part of its mission, the Center plans to develop technologies to identify and separate scrap materials from waste streams and build strategies and technologies to enable greater scrap utilization within materials processes. Current research activities include efforts focused on REE recycling.
- With a possible $2.5 M in funding from the EPA, the UN has initiated a new project that will track discarded mobile phones and other electronic wastes generated in the United States in order to develop solutions aimed at recovering REMs (and other materials) from the equipment through proper recycling. In addition to the United States, the project includes international partners (Dillow, 2011).
- The government of Japan has instituted subsidies and facilitated inter-industry cooperation, both with the goal of encouraging REE recycling. Japan's Ministry of Economy, Trade and Industry has published a list of five main focus areas designed to ensure a stable supply of REEs. These focus areas include: (1) accelerating the development of alternatives to REEs; (2) positioning Japan as a global hub for REE recycling; (3) working with manufacturers to install equipment that would result in reduced REE consumption; (4) providing support to companies trying to acquire rights to REE mines outside of China; and (5) investigating the feasibility of stockpiling REEs (Hosaka, 2010). In support of these initiatives, the Ministry of Trade has provided a third of a billion dollars in subsidies, which has been used as seed money for 160 projects. Future funding will increase as the Japanese government is offering another 110 million dollars in subsidies in the next fiscal year. The Japanese have set a goal of reducing the amount of rear earths imported by its domestic industry by one-third (Kidela Capital Group, 2011) In addition, another source reports that Japan has made recycling of rare earth minerals mandatory (Baudzus, 2011).
- South Korea has plans to spend $15 million by 2016 as part of a long-term policy for securing rare earths. The policy, titled "Plans for Stable Procurement of Rare Metals," was scheduled to be finalized in 2010 and to include strategies related to developing mines, investing in alternative materials, and recycling technologies (Hosaka, 2010).

- In the European Union, there is a new law that requires car and electronic manufacturers to start recycling rare earth minerals (Baudzus, 2011). The European Commission also has adopted a new strategy targeted at better utilization of supplies in the EU, partnership with new sources (with Africa as the key focus), and increased recycling. In addition, Germany has passed its own strategy specifically designed to ensure that it is able to secure enough rare earths to support manufacturing operations. The strategy includes developing partnerships with countries that produce rare earths and is also designed to encourage recycling (Bloomberg Businessweek, 2010).

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6. Potential Human Health and Ecological Risks of Production, Processing, and Recycling of REEs

Since the early 1990s, EPA has performed a number of studies to evaluate the environmental risks to human health and the environment from hardrock mining and metal ore processing activities. The most significant environmental impact from contaminant sources associated with hard rock mining is to surface water and ground water quality. However, documented impacts have also occurred to sediments, soils, and air. Comparisons can generally be made for mining of rare earth mineral ores and processing those ores into the final products with other hard rock metal mining and processing operations. These comparisons are suggested at a high level relative to the typical waste streams that are produced by a hardrock mine. Although process waste streams and sources are explored from past practice, direct comparisons are not attempted at an operational level since every deposit is geochemically unique and every mine and processor must conform to the characteristics of the ore deposit. These environmental and human health impacts are largely associated with the release of mine waters that typically contain elevated concentrations of metals, industrial chemicals used to maintain the mine site and equipment, and processing chemicals needed for milling and final processing steps. However, the specific health effects of elevated concentrations of REEs in the environment are not well understood. There is also potential for impacts to human health and the environment from recycling activities to recover REMs. This section presents a general conceptual site model (CSM) for a generic, aboveground hardrock mine site.

Mining and processing activities have the potential to create a number of environmental risks to human health and the environment. The severity of these risks is highly variable between mine and mine plant operations. The contaminants of concern will vary depending on the REE-mineral ore, the toxicity of the contaminants from the waste rock, ore stockpiles, and process waste streams. The mobility of contaminants will be controlled by the characteristics of the geologic, hydrologic, and hydrogeologic environments where the mine is located, along with the characteristics of the mining process and waste handling methods. The environmental impact from urban mining or REM recycling operations is similar to mineral processing, since recovery and refining methodologies can be identical.

A summary of the potential emission points and pollutants of concern associated with mining, processing, and recycling REEs are presented in **Table 6-1.**

Table 6-1. Summary table of pollutants, impacted environmental media, emission sources, and activity associated with REE mining, processing, and recycling.

Activity	Emission Source (s)	Primary Pollutants of Concern
Mining (aboveground and underground methods)	Overburden Waste Rock Sub-ore Stockpile ▪ Ore Stockpile	Radiologicals Metals Mine Influenced Waters/Acid Mine Drainage/Alkaline or neutral mine drainage Dust and Associated Pollutants
Processing	▪ Grinding / Crushing	▪ Dust
	▪ Tailings ▪ Tailings Impoundment ▪ Liquid Waste from Processing	▪ Radiologicals ▪ Metals ▪ Turbidity ▪ Organics ▪ Dust and Associated Pollutants
Recycling	▪ Collection	▪ Transportation Pollutants
	▪ Dismantling and Separation ▪ Scrap Waste ▪ Landfill	▪ Dust and Associated Pollutants ▪ VOCs ▪ Metals ▪ Organics
	▪ Processing	▪ Dust and Associated Pollutants ▪ VOCs ▪ Dioxins ▪ Metals ▪ Organics

In general, limited toxicological or epidemiological data are available to assess the potential human health effects of REEs. A preliminary literature search was conducted to identify human health, epidemiology, and toxicity studies on REEs. The identified literature was briefly reviewed and summarized in tables provided later in this section.

6.1 Generalized Conceptual Site Model for Environmental Risk from a REE Mine and Mineral Processing Plant

This section provides a generic Conceptual Site Model (CSM) to illustrate and provide general perspective for common sources of contamination along with typical contaminant release, transport, and fate scenarios that could be associated with a larger hardrock mine site. It attempts to describe the sources of contaminants, the mechanisms of their release, the pathways for contaminant transport, and the potential for human and ecological exposure to chemicals in the environment

As in other parts of this document, the discussion presented here is general and cannot specifically address every circumstance or condition. However, to reiterate a previous point: while the geochemistry of the ore, and therefore the characteristic of pollutants, is likely quite different, a REE mine is similar to many other hardrock mining operations and the methods used to beneficiate and mill REE-mineral ores are also similar. While the basic metallurgical processes used to extract a metal from hardrock mineral ores are similar, the actual mineral ore processing steps used to recover a metal or metal oxide are varied. Metallurgical processing is generally unique to the deposit's geochemistry, and therefore the actual methods and chemicals used are often proprietary. Environmental impact occurs at every stage of the mines life-cycle.

The CSM presented in the discussion assumes that within the property boundaries of a single mine there can be a variety of support process areas and facilities. Waste materials are associated with each step of mining and the subsequent ore processing steps used in extraction metallurgy for the target metal. In general, the waste streams from mining and mineral processors can include sediment, particulates, vapors, gases, wastewater, various chemical solvents, and sludge from chemical extraction and filtration steps. Most mining and processing operations will produce these and/or other wastes that require management and have the potential to create environmental risks to human health and sensitive habitat.

The CSM provided in **Figure 6-1** shows a mining and processing site of nonspecific location, climate, and physical setting. Mine conditions, ore geochemistry, and geologic, physiographic, and hydrogeologic settings where the mine is located will define many of the factors that influence the likelihood and potential severity of environmental risks associated with a specific mine site. This CSM is provided for general perspective and to orient the reader who is unfamiliar with the site features and conditions generally found at a commercial hardrock mine site. The features illustrated in the CSM include mine pits, leach piles, other processing areas, tailings, and waste piles.

As previously discussed in this document, mining is the removal of ore from the ground on a large scale by one or more of four principal methods: surface mining, underground mining, placer mining, and in situ mining (extraction of ore from a deposit using chemical solutions). After the ore is removed from the ground, it is crushed so that the valuable mineral in the ore can be separated from the waste material and concentrated by flotation (a process that separates finely ground minerals from one another by causing some to float in a froth and others to sink), gravity, magnetism, or other methods, usually at the mine site, to prepare it for further stages of processing. The production of large amounts of waste material (often very acidic) and particulate emission have led to major environmental and health concerns with ore extraction and concentration. Additional processing separates the desired metal from the mineral concentrate.

The CSM shown in Figure 6-1 illustrates that there are various receptor types around the mine site at different times during the life cycle of the mine:

- **Construction worker** – May be exposed for short or extended periods depending on role and responsibilities; levels of exposure differ depending on mine's life-cycle stage when work is performed and location of work relative to source.
- **Outdoor worker** – Experiences potential exposure from dust, radiologicals, and hazardous materials.
- **Indoor worker** – Experiences either less exposure if in office spaces or potentially more exposure if inside process areas.
- **Off-site tribal practitioner** – Assumed that tribal peoples may use traditional hunting and fishing areas for some level of subsistence.
- **Recreational user -** May use lakes, streams, or trails near the mine site or recycling facility and may also boat, swim/wade, bike, hike, camp, hunt, fish or subsist temporarily in the area.
- **Agricultural worker** – May experience more exposure from dusts, noise, or impacted water supply.
- **Trespasser** – Exposure dependent upon mine site life-cycle stage and activity while on-site.
- **Off-site resident** – Exposure would depend upon mine site life-cycle stage and distance from potentially multiple source areas; routes could be air, ingestion of dust or native or gardened plant or animal, ingestion of contaminated water, and dermal contact with soil or water.
- **On-site resident** – Exposure would occur after mine land is reclaimed and re-developed for residential use. Routes of exposure could be air, ingestion of dust or native or garden plant or native animal, ingestion of contaminated water, and dermal contact with soil or water depending

on residual concentrations remaining in un-reclaimed source areas or in yard soil if mine wastes were mixed with clean soil and used as fill.

- **Ecological receptors** – Aquatic and terrestrial.

Direct exposure can occur as a result of direct contact with solid phase mine or process wastes. General protections at mine sites are typically required, especially those located on federal lands. For example, fencing is generally required for isolating mine site areas where certain leaching chemicals are used to protect and prevent the direct exposure of the public, wildlife (including migratory birds), and livestock. Indirect expose to humans can occur through the food chain by, for example, the consumption of meat from exposed fish, shellfish, wild game, grazing farm animals, or by consuming vegetables grown in contaminated soils.

The EPA stipulates in its risk guidance (1989) that a completed exposure pathway must contain the following elements:

- Source and mechanism for release of chemicals
- Transport or retention medium
- Point of potential human contact (exposure point) with affected medium
- Exposure route (e.g., dermal contact, inhalation, or ingestion) at the exposure point

If any one of these elements is missing, then no human health or ecological risk exists. The CSM presented in Figure 6-1 shows a simplified model of the chemical transport pathways for the site. The ten receptor types (listed above) are shown in the CSM along with likely exposure routes.

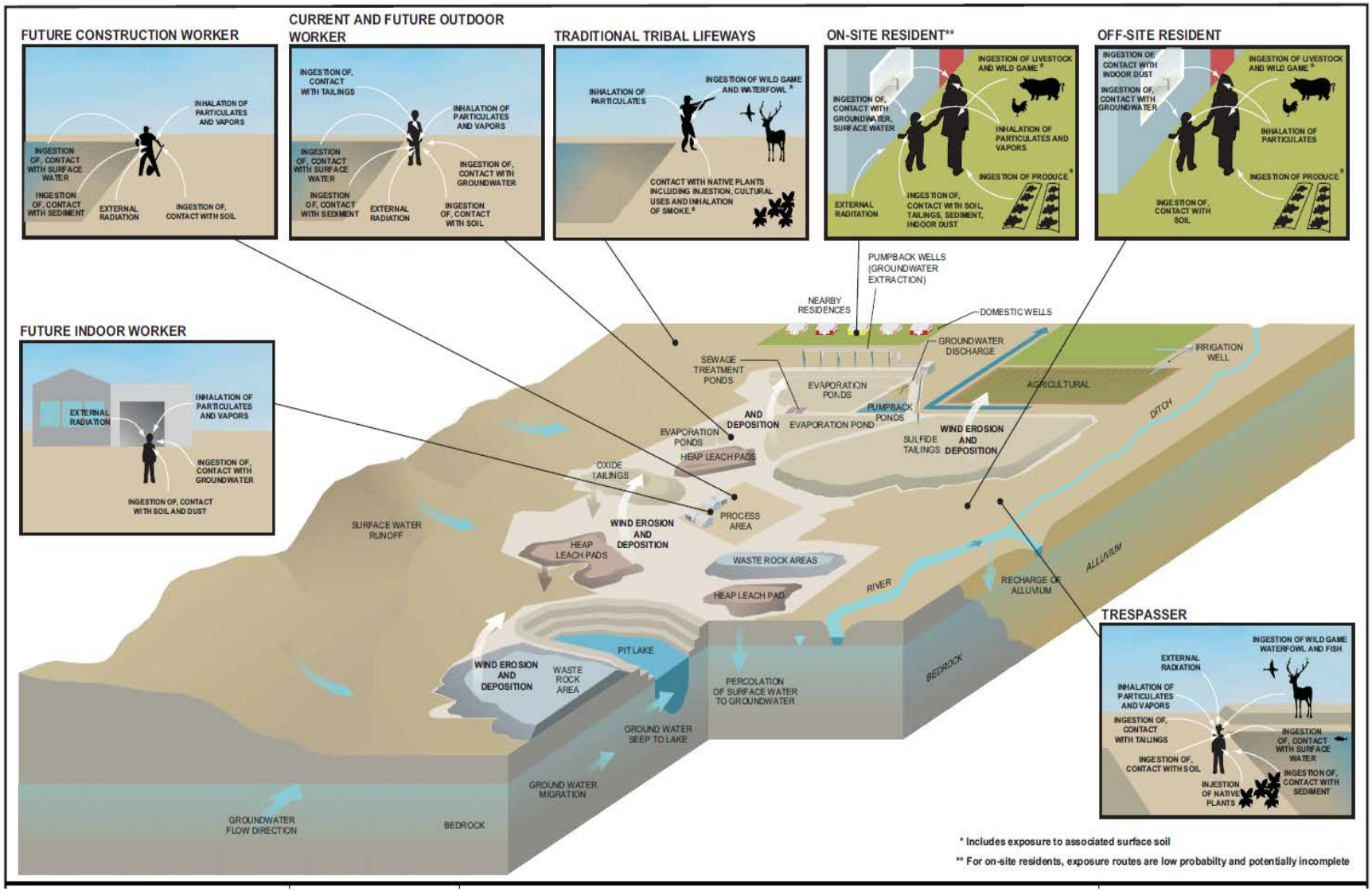

Figure 6-1. Generic above-ground hardrock mine conceptual site model and exposure pathways (U.S. EPA, 2009a).

6.1.1 Contaminant Release and Transport

The environmental behavior of mine/ore materials, REE-containing minerals, and the mineralogy of overburden and waste rock can vary significantly. Some of the potential effects include alteration of wildlife habitats, erosion, sedimentation, generation of windblown particulates, pollutant loading to groundwater and surface water, losses of chemical solutions from process areas, and surface subsidence. Generally, the specific areas of concern arise from sediment loading, metals contamination, toxic chemical release, and acidification.

6.1.1.1 Surface Water and Ground Water Pathways

Surface Water

In addition to mining and processing activities, exploration activities can initially impact surface water and groundwater resources at the site. The potential impacts that could occur during this phase of a mine's life are variable and are influenced by location; impacts in densely forested areas will be different than the impacts to sparsely forested and arid regions. Ore bodies located in more remote locations may require an extensive network of access roads to drilling sites that result in the removal of habitat and alteration of terrain by removing soil and rock to create a stable road bed. Where water bodies exist along these constructed unpaved access roadways, or the drilling sites, pollution to streams and other water bodies can potentially become problematic. Additional runoff from clearing or other land alterations can increase normal stream flow during rainfall events, which increases the potential for downstream impacts from flooding. These types of impacts are more pronounced the closer the access roadways are constructed to the water body and the greater the area cleared.

Drilling fluids from exploration activities can have significant impacts to aquatic environments or shallow groundwater if discharged or accidentally released to the environment. Suspended and dissolved solids concentrations would potentially overwhelm a small stream. The drilling fluids are managed at the borehole, either in a constructed mud box or in a pit. After the borehole is completed, the drilling fluids may be contained in drums for disposal, moved to an on-site waste management area (e.g., a landfill), dispersed at a land application unit (i.e., landfarming or landspreading), or stabilized in the mud pit and buried in place. Recycling of the drill cuttings is a common practice (i.e., road spreading and on-site construction base material), but additional uses are being tried in some sectors, such as the use of drilling mud and cuttings for use as substrate for wetland revitalization (Argonne National Laboratory, 2011). During any phase of mining operations, water bodies may receive increased sediment loads from erosion of freshly exposed soils that can cause decreases in available oxygen content of waters and decrease light penetration for photosynthesis to occur for aquatic plants.

Erosion of rock surfaces, especially where sulfide minerals are present, can cause a natural acidification of runoff water (i.e., acid rock drainage or ARD) that can affect surface water bodies. Acid mine drainage (AMD) and neutral mine drainage (NMD) exacerbates the problem of releasing metals from mined materials and surfaces in addition to naturally occurring ARD. AMD occurs when oxide ore minerals (metalliferous minerals) are altered by weathering, rainwater, and surface water into oxides or sulfides. AMD usually is not a significant issue for REE deposits; however, the rock that surrounds or is overlying an ore body may contain the sulfide minerals that could create AMD. REEs often occur in ores rich in carbonate minerals, which can help buffer any effects of AMD that might occur; however, aquatic systems are very sensitive to changes in pH and increases in alkalinity can also be problematic. While AMD can result in metal toxicity problems, divalent metals are generally less toxic at higher pH and in more mineralized waters associated with NMD. AMD and NMD are collectively referred to as mining-influenced water (MIW). Because the surface area of mined materials is greatly increased, the rate of chemical reactions that generate AMD, or increase alkalinity is also greatly increased. MIW can occur from stockpiles, storage piles, and mined or cut faces that can potentially impact local soil, groundwater,

and surface water quality. Typically, drainage from these management areas is controlled, but releases can potentially happen due to overflows during storm events, liner failure, and other breaches of engineered controls.

Aquatic organisms will generally only tolerate a narrow fluctuation in the acidity or alkalinity of the natural system until reproductive capacity is diminished or mortally occurs. Erosion of exposed rocks can cause an increase (more acidic) or decrease (more basic) in the hydrogen ion concentration (pH) of the aquatic environment. Prior to mining, oxidation is a function of natural weathering, and any acid generation (i.e., acid rock drainage), or increases in alkalinity, occurs very slowly. Soils and riparian areas help to mitigate AMD and MIW, but these buffer zones are usually missing from the mining site unless maintained or constructed. However, as previously noted, acid mine drainage is not a significant issue that is typically associated with REE-deposits.

Potential impacts to surface waters from mining operations can be mitigated. Maintaining buffer zones between stream areas and areas of exploration and mining activity can help to control runoff to streams. Capturing and containerizing drilling fluids also can mitigate impacts to streams, groundwater, and nearby habitat. Excavated soils, rock, and dry cuttings, either from mine areas or drilling activities, can also be controlled to prevent release of sediments and contaminated runoff.

Groundwater

Groundwater and surface water interactions are common in the hydrogeologic cycle. At mining sites, those interactions are often enhanced. Groundwater can migrate to existing mine pit lakes or evaporation ponds, or be recharged from surface mine units. Mine pit water is generally removed to evaporation ponds or treated and discharged to surface waters or injected into the aquifer. It also is often used in the milling processes. Water may flow out of and transport chemicals from mine pit lakes into alluvial and bedrock groundwater flow systems, particularly during periods of high precipitation. Groundwater inflow to pit lakes, streams, buried trenches, or surface ditches may also result in the transport of chemicals from subsurface environments to surface waters, including the transfer of chemicals in suspended sediments.

Pumpback well systems are sometimes used to extract a portion of mineralized groundwater or pit seepage water that could migrate off-site and impact neighboring or nearby human or ecological receptors. The effluent is then pumped and released to lined evaporation ponds, resulting in an accumulation of potentially contaminated sediment. Chemical precipitate accumulations can also occur in active pumpback water systems and evaporation ponds. Losses of dewatering effluent from pipelines carrying water from mine pits, holding ponds, or from pumpback water systems can be a potential source of soil and groundwater contamination.

Examples of Environmental Damages to the Aquatic Environment

There is one CERCLA site within the Blackfoot River sub basin where REE-containing mineral deposits were mined (U.S. Forest Services, 2011). An Administrative Order of Consent for South Maybe Canyon Mine Site was entered into by the U.S. Forest Service and Nu-West Mining, Inc., in June 1998. The primary reason for the order was the release of hazardous substances, including selenium, from the site into groundwater and surface waters above Idaho state water quality standards. It should be noted that rare earth metals were not identified as hazardous substances that had been released from the site. The South Maybe Canyon Mine was developed for the production of phosphate, and REEs were recovered as a byproduct (Long et al., 2010). This mine has been identified as a possible source of REEs for future development.

In March 2010, the EPA imposed administrative penalties against Upland Wings, Inc. for Clean Water Act violations at the former Pea Ridge Mining Operation in Washington County, Missouri. Violations

were associated with the discharge of metals and other constituents (i.e., oil and grease, copper, chromium, cadmium, iron, lead, and total suspended solids) in concentrations that exceeded permitted levels. Earth-moving equipment was also used to dredge iron ore tailings from settling ponds and to dispose of the materials in a nearby creek without a permit that affected nearby wetlands.

6.1.1.2 Air Pathway

Fugitive Dust

Direct exposure of humans can occur from inhalation of fine dusts (i.e., particulates) or by ingestion or dermal contact of contaminated dusts. Particulates or fugitive dust from storage piles, conveyor systems, site roads, or other areas can be transported by wind and may be deposited and accumulated in downwind areas, including surface soils and surface water bodies (e.g., ponds, pit lake), or be inhaled by site workers and nearby residents. Dust can be an irritant, a toxicant, or a carcinogen, depending on the particles' physicochemistry, and can be composed of inorganic and organic chemicals. However, the presence of physical barriers, such as vegetation or structural foundations, may dampen or reduce the transport of particles as wind-blown dust. Accumulated mine sediments or dust may become secondary sources of chemicals transported to groundwater via leaching and percolation.

Aerosols and Chemical Vapors

Mine workers can be exposed to aerosols from numerous processes, including comminution (i.e., the process in which solid materials are reduced in size by crushing, grinding, and other techniques), re-entrainment (i.e., air being exhausted is immediately brought back into the system through the air intake and/or other openings), and combustion sources. Aerosols are dispersed mixtures of dust and/or chemical-containing water vapor. Cutting, drilling, and blasting of the parent rock, especially in underground mines, creates aerosols with a composition similar to the parent rock. As previously discussed, comminuting the ore underground is sometime practiced for efficient transport out of the mine area, and aerosols can accumulate in these areas. The dusts from ore mineral liberation and separation steps settle to other areas such as ventilation systems, roadways, work areas, and nearby surrounding areas. Aeration ponds are sometimes used to treat waste waters on a mine site, and the aerators used to disturb the surface of the water can create aerosols; the problem can become worse if surfactants are used and not managed properly. Aerosols can potentially accumulate along perimeter areas of ponds and lagoons and contaminate soils, sediments, surface water, and shallow groundwater through deposition and transport.

Radioactivity

Lanthanides and yttrium are recovered primarily from ores and minerals that naturally contain uranium and thorium; however, some level of radioactive materials is found in association with many REE deposits. As a result, the waste rock and sludges from the extraction of rare earths also contain these radionuclides and are considered Technologically-Enhanced, Naturally-Occurring Radioactive Materials (TENORM). TENORM wastes contain radionuclides in concentrations that could give rise to unacceptable radiation levels. The EPA has estimated that levels of naturally occurring radioactivity contained in common rare earth (e.g., monazite, xenotime, bastnasite) deposits in the United States range from 5.7 to 3,224 picoCuries per gram (pCi/g). The USGS has estimated uranium and thorium content of minerals found in REE deposits. Additional information can be found in Long et al., 2010. Radioactive elements, such as thorium and uranium, can concentrate in mining dusts and sediments that must be managed. Radon gas can also be emitted from these sources. Transport of particulates containing uranium and thorium may occur by any of the transport pathways described above. Acidic groundwater and surface water and low concentrations of organic material in soils can contribute to the mobility and transport of radioactive materials. Accumulations of sediments deposited by runoff and dusts also can concentrate radioactive materials. External exposure to naturally occurring radiation and radon gas is often limited to soil or waste materials that are within several inches of the ground or pile surface;

radioactive materials found deeper in the soil column or accumulated sediments are generally shielded by the top layer of soil. Geometric attenuation generally limits the external radiation from naturally radioactive materials with no interposed shielding materials to within a few meters (i.e., less than 5 meters and often less than 1 to 2 meters from the source). Radioactivity can become concentrated in mineral scales that develop in groundwater recovery wells, holding tanks, aeration ponds, and milling processes areas. Inhalation of contaminated dusts is generally of greatest concern for naturally occurring radioactive materials.

Tailings storage facilities typically receive the bulk of processing water, which is normally recycled, but some of it could be released into the environment through seepage or overflows due to unusually high rainfall. The tailings storage facilities (TSF), when dry, usually represent the main source of radon/thorium and dust emissions to the environment. Special containment arrangements are required for the disposal of tailings generated during chemical and/or thermal processing of uranium and thorium-bearing minerals to ensure that environmentally mobile radionuclides are not released into the surrounding environment. The disposal of contaminated equipment and materials also needs to be controlled. In addition, the possibility of off-site contamination from trucks and equipment moving off-site needs to be considered.

After milling and concentrating, the mineral is sometimes stockpiled at the mine site prior to transport to the processing sites, and these stockpiles may contain radioactive minerals in concentrations sufficient to produce elevated radiation levels and radon. The stockpiles, therefore, need to be protected against unauthorized access and also against the possibility of the material spreading through wind saltation. Ideally, stockpiles containing radionuclides in concentrations that require signposting of areas as “supervised” and/or “controlled” should be located on a concrete slab to simplify the management and clean-up operations.

The tailings from the separation and downstream processing of minerals may contain radionuclides in concentrations that could give rise to unacceptable levels of radiation and radon. Appropriate management is typically required, and the disposal of the waste will depend on the method used to process the mineral and on the respective levels of radiation and the concentration of radon gas emitted. The possibility of ground water contamination increases if chemical and/or thermal treatment of the mineral occurs (e.g., in the case of separating the heavy mineral sands). Otherwise, the radionuclides in the tailings could be considered as remaining bound in the individual mineral grains; therefore, the possibility of the contamination of groundwater by radionuclides from tailings is not considered to be less significant. Radium may be present in the tailings water, which would require removal before being disposed.

Where any grinding, chemical, and/or thermal treatment of minerals containing radionuclides takes place, additional safeguards must be implemented due to the fact that secular equilibrium in both uranium and thorium decay chains may be disrupted. This could result in an increased environmental mobility of radionuclides, such as radium and radon. Cleaning of certain minerals prior to processing (such as, for example, the cleaning of the heavy mineral sand grains) may produce finely powdered waste (slimes). Slime wastes may have significant uranium or thorium content, and the disposal as radioactive waste may be required.

The equipment used in downstream processing of minerals often becomes contaminated by NORM or TENORM. Contaminated equipment must either be disposed of properly, or thoroughly decontaminated prior to any re-use. Scales and sludge build on the inside surfaces of pipes and vessels used in chemical and thermal processing, and these materials often have elevated levels of radionuclides.

Regulation and guidance vary among federal agencies and organizations for the handling of TENORM waste and the associated environmental and health risks. The EPA (2000) began to address this issue in its work with the National Academy of Sciences in 1999. However, work is on-going to streamline policy and guidance related to TENORM.

Example of Environmental Damage from Radioactivity

An example of issues associated with radionuclides from the production of rare earths is occurring in Malaysia. According to a Physorg.com news article (Zappei, 2011), international experts are currently investigating whether a refinery being built by an Australian mining company, Lynas Corp. Ltd., to process rare earth minerals in Malaysia presents any threat of radioactive pollution. Malaysia's last rare earth refinery in northern Perak state was closed in 1992 following protests and claims that it was the source of radionuclides that were identified as the cause of birth defects and leukemia among nearby residents. The refinery is one of Asia's largest radioactive waste cleanup sites. The Pahang plant is meant to refine slightly radioactive ore from the Mount Weld mine in Western Australia, which will be trucked to Fremantle and transported to Malaysia by container ship. Lynas plans to begin operations at the refinery late in 2011 and could meet nearly a third of world-wide demand for rare earths, excluding China.

Similar issues are being addressed for proposed rare earth production in the United States. Thorium waste will be produced along with rare earths mined from the proposed operations at Pea Ridge, Missouri. The owners of the mine have proposed to construct a rare earth refinery and regional thorium stockpile along the Mississippi River near St. Louis (Lambrecht, 2011). It is believed by the proponent that the thorium storage facility will help address environmental liability concerns in the production of rare earths. The thorium would be stockpiled in anticipation of using it for nuclear power production. Currently, the United States does not have a thorium fuel cycle, but China is reported to have thorium reactors in operation. Public concerns raise the issue of site clean-up that has occurred at former thorium production facilities once operated by the DOE.

6.1.2 EPA Studies of Hardrock Mine Environmental Risks

Generalized risk information is presented below from past studies of hardrock mines. The geologic environments where other types of metal mines are developed are often similar to geologic settings where REEs are found. In addition, mining and processing operations are similar to other hardrock mines. Therefore, past information gather by EPA to characterize the risks from hardrock mines is likely relevant to the risks from the mining of REEs.

6.1.2.1 Environmental Impacts from CERCLA Sites

Collected human and ecological risk information (U.S. EPA, 2011d) was summarized from a subset of 25 National Priority List hardrock mining and mineral processing sites by EPA and is presented here in relation to risks that could also be typical from a hardrock mining operation for REEs. The summary of the contaminant sources, primary transport media or pathway, routes, and the receptors is provided in **Figures 6-2** (human receptor) **and 6-3** (ecological receptor). The sample set of NPL sites represents those listed on the NPL post-1980, and it is thought that these sites likely represent the conditions that could be found at modern mine sites. It could then be expected that similar source, fate, and transport scenarios could be related to REE mining and processing facilities.

CONTAMINANT RELEASE → CONTAMINANT TRANSPORT → CONTAMINANT FATE

NPL Sites

SOURCES

Acid Mine/Rock Drainage
Asbestos Fibers
Demolition Dumps
Deposition
Dredged Sediments
Flue Dust
Fugitive Dust
Housekeeping Debris
Incinerator Ash
Iron-rich Liquid Acid
Metal Ore
Non-Contacting Cool Water Effluent
Ore Slimes
Ore/Nodule Stockpiles
Overburden
Overburden
Potliners
Pressing Ponds
Process Fluids
Process Stacks Emissions
Quartzite Dust Slurry
Radioactive Waste Piles
Run-off
Sewage Sludge
Storage Tanks
Sulfate Residuals
Waste Tailings
Transformers
Treater Dust Stock Piles
Underflow Solids Piles
Unlined Pits
Waste Drums
Waste Piles
Waste Rock

PATHWAYS

Groundwater
Sediment
Soil
Surface Water
Vadose Zone

ROUTE

Dermal Contact
External Radiation
Ingestion of
- Food-Plants
- Food-Birds
- Food-Mammals
- Food-Terrestrial
- Food-Benthic
- Food-Fish
- Food-Aquatic Plants
- Food-Aquatic

Inhalation
Combined Routes

RECEPTORS

Occupational (Agricultural)
Occupational (Construction)-Current
Occupational (Construction)-Future
Occupational (Dredging)-Future
Occupational (Industrial)-Current
Occupational (Industrial)-Future
Occupational(Not Specified)-Current
Occupational(Not Specified)-Future
Recreational-Current
Recreational-Hiker
Residential-Current
Residential-Future
Site Visitor
Trespasser-Current
Trespasser-Future

Removal Sites

SOURCES

Adit Drainage
Adits
Condenser Waste
Manual/Aerial Deposition
Mill Foundation
Mill Tailings
Mine Waste
Overburden
Raffinate Leachate
Tailings
Vat Leachate Tailings
Waste Drums
Waste Rock Piles
Water Drainage

PATHWAYS

Air
Groundwater
Soil
Surface Water

ROUTE

Dermal Contact
Inhalation
Ingestion

RECEPTORS

Occupational
Recreational-Current
Residential-Current
Trespasser-Current

Figure 6-2. Sources of potential human exposures resulting from mining operations (U.S. EPA OCRC, 2010).

CONTAMINANT RELEASE → **CONTAMINANT TRANSPORT** → **CONTAMINANT FATE**

SOURCES

Adit Drainage
Adits
Airborne Emissions
ARD
Process Residues
Process Stacks Air Emissions
Quartzite Dust Slurry
Run-off
Condenser Waste

Debris
Exposed Mineralized Bedrock
Fuel/Oil
Fugitive Dust
Leachate
Manual/Aerial Deposition
Mine Waste
Municipal Waste
Nodule Stockpiles
Non-Contacting Cool Water Effluent
Ore Stockpiles
Overburden
Phossy Water
Potliners

Sludge
Spent Mineral Waste
Spent Ore
Tailings
Treater Dust Stock Piles
Underflow Solids Piles
Vat Leachate Tailings
Waste Drums
Waste Piles
Waste Rock
Wastewater
Water Drainage

PATHWAYS

Food-Aquatic Invertebrates
Food-Aquatic Plants
Food-Benthic Invertebrates
Food-Birds
Food-Fish
Food-Mammals
Food-Plants
Food-Terrestrial Invertebrates
Food-Terrestrial Plants
Groundwater
Plants
Sediment
Soil
Soil Invertebrates
Subsurface Soil
Surface Soil
Surface water
Water

ROUTE

Dermal Contact
Ingestion
Inhalation
Combined Routes

RECEPTORS

Birds

American Dipper
American Kestrel
American Robbin
Barn Owl
Belted Kingfisher
Bobwhite Quail
Carnivorous Birds
Cliff Swallow
Great blue heron
Horned Lark
King Fisher
Mallard
Migratory Birds
Mountain Chickadee
Northern Harrier
Omnivorous Birds
Pine Grosbeak
Red-tailed Hawk
Red-tailed Hawk
Sage Grouse
song sparrow
spotted sandpiper
Waterfowl
Woodcock

Mammals

Carnivorous Mammals
Coyote
Deer
Deer Mouse
Deer Mouse
Field Mice
Herbivorous Mammals
Long-tailed Weasel
Masked Shrew
Meadow Vole
Mink
Montane Vole
Omnivorous Mammals
Piscivorous Mammals
Rabbits
Raccoon
Red Fox
Small mammals
Soil Invertebrate-feeding Mammals
White-tailed Deer

Other

Amphibians
Benthic Invertebrates
Benthic macroinvertebrates
Benthic Organisms
Deepwater Habitats
Fish
Future-Aquatic Organisms
Future-Wetland Invertebrates
Future-Wildlife
Herbivores
Macroinvertebrates
Periphyton Community
Pets
Plants
Predatory Fish
Rainbow Trout
Sagebrush
Soil invertebrates
Terrestrial Invertebrates
Terrestrial Organisms
Terrestrial Plant Community
Terrestrial Soil Community
Thickspike Wheatgrass
Transient Organisms
Vegetation

Figure 6-3. Sources of potential exposures of current and future ecological receptors resulting from mining operations (U.S. EPA ORCR, 2010).

From a previous study (U.S. EPA, 1995) of risks to human health and the environment from hardrock mines, it was concluded that the 66 hardrock mining cases illustrated that significant human health and environmental damages were caused by the management of wastes from mining and mineral processing, particularly placement in land-based units. Molycorp Minerals rare earth mine in Mountain Pass, CA, was one of the sites included in the study. Wastes subject to the RCRA Bevill Amendment were found to be the cause of the damages. These damages occurred in all hardrock mining sectors and across all geographic regions of the United States. **Table 6-2** excerpted from the report summarizes the type of impacts.

Table 6-2. Frequency of Various Types of Impacts from CERCLA Sites (U.S. EPA, 1995)

Type of Impacts	Portion of Damage Cases (Total NPL Sites = 66)
Surface water contamination	70 percent of cases
Ground water contamination	65 percent
Soil contamination	50 percent
Human health impacts	35 percent
Flora and fauna damage	25 percent
Air dispersion or fugitive emissions	20 percent

6.1.2.2 Acid Mine Drainage at CERCLA Sites

In another review by EPA of 156 hardrock mine sites, the results showed that approximately 30 percent (or about 45) of the sites had problems with acid mine drainage (U.S. EPA, 2004). The report also suggested that acid mine drainage occurred most often in EPA Regions 8, 9, and 10. The EPA OIG (2004) also reiterated the concern from the National Wildlife Federation that sites where AMD is present should be carefully monitored as "the presence of acid mine drainage is either underestimated or ignored until it becomes evident, at which time the costs often exceed the operator's financial resources, leading to bankruptcy or abandonment of the site in many cases." As previously stated, it is not anticipated that the mining of REE will typically produce AMD given the typical geochemistry of these deposits.

6.1.2.3 Prospective REE Mining Sites and CERCLA Review

A comparison of USGS (Orris et al., 2002) data and EPA CERCLA documents revealed four mines that have been damage case sites. While these sites are not yet being mined for REEs, they have been identified as potential future sources:

- Maybe Canyon Phosphate Mine (Superfund site);
- Mountain Pass REE Mine (when owned by Union Oil Company of California (Unocal); not to be confused with current owner, Molycorp Minerals, LLC);
- Smoky Canyon Phosphate Mine (Superfund site); and
- Bokan Mountain Uranium Mine (not on NPL but Federal Facilities review site).

Releases of radionuclides were the environmental impacts that were investigated for both Mountain Pass and Bokan Mountain mines. Maybe Canyon Mine was in operation between 1977 and 1984. Approximately 120 acres of waste rock (29 million cubic yards) was present from which selenium and other hazardous substances were reported to have contaminated ground water and surface water (U.S. Department of Agriculture, 2011). Selenium contamination is a common problem at phosphate mines and it was also found to be an environmental contaminant of concern at the Smoky Canyon Mine.

6.2 Pathway and Exposure Scenarios for REE-Recycling

During collection of items to be recycled, exposure to hazardous materials is likely to be minimal and, if occurring, will likely result from either dermal or inhalation exposures to materials released from damaged items. Similarly, when done properly, manual dismantling is likely to have a low potential for worker risks resulting from exposure to hazardous materials. Mechanical dismantling and shredding can generate dust containing hazardous components. If not properly controlled, the dust can result in inhalation or dermal exposures to workers. Dust control is particularly important when the items being shredded contain brominated flame retardants, because high temperatures during shredding could result in the formation of dioxins (Schluep et al., 2009).

Leaching processes using liquids such as nitric acid or aqua regia can cause release of nitrogen oxide or chlorine gases and therefore must be controlled to prevent human and environmental impacts. In other processes that use strong acids or bases, safe handling of chemicals and disposal of resulting waste streams is important to protect workers and the environment. Thermal processes used for recycling can result in air emissions, liquid wastes, and solid waste streams. As for mineral processing, TENORM is a safety and environmental concern related to the recycling of metals. Again, proper controls and handling are necessary to prevent human exposures and environmental impacts.

As reported by Schuler et al. (2011), when compared with primary processing, recycling of REEs will provide significant environmental benefits with respect to air emissions, groundwater protection, acidification, eutrophication, and climate protection. This report also states that the recycling of REEs will not involve the majority of the impacts from mining operations and the impacts that can result from radioactive impurities, as is the case with primary production of metals. As previously noted in ***Section 5***, a large percentage of REE-containing materials are shipped to developing countries where they are recycled using informal processes. These informal operations can include manual dismantling, open burning to recover metals, de-soldering of printed wiring boards over coal fires, and acid leaching in open vessels, as illustrated in **Figure 6-4**. In almost all cases, these operations are uncontrolled and can lead to human exposure and extensive environmental damage. In addition, the processes used are generally less efficient and result in lower materials recovery than from more formal or established methods. Environmental regulations would prevent these types of uncontrolled REE recycling and metal recovery operations from establishing in the United States.

Figure 6-4. "Low–tech" gold recycling in Bangalore/India (Schluep et al., 2009).

6.3 Documented Human Health and Ecological Effects from Exposure to REE

In general, limited toxicological or epidemiological data are available to assess the potential human health effects of REEs. A literature search was conducted to identify human health, epidemiology, and toxicity studies on REEs. The identified literature was briefly reviewed and summarized in tables provided later in this section. Many studies examined mixtures of REEs, rather than individual elements. Respiratory, neurological, genotoxicity, and mechanism of action studies were identified. As evidenced by additional literature cited in secondary sources, an additional literature search should be conducted and the literature review summaries presented here should not be considered comprehensive. Many studies were conducted by Chinese investigators and are not available in English (only the abstracts were available in English).

REEs are broadly grouped into "light" (La, Ce, Pr, Nd, Sm, Eu, and Gd) and "heavy" (Y, Tb, Dy, Ho, Er, Tm, Yb, and Lu) classes (Wells and Wells, 2001, as cited by U.S. EPA, 2009b, 2009c, 2009d). For any given lanthanide, soluble forms include chlorides, nitrates, and sulfates, while insoluble forms include carbonates, phosphates, and hydroxides. The larger, lighter (smaller atomic number), and less soluble ions have been observed to deposit primarily in the liver, while the smaller, heavier (larger atomic number), and more soluble ions are similar in ionic radius to divalent calcium and distribute primarily to bone (Wells and Wells, 2001, as cited by U.S. EPA, 2009a, 2009b, 2009c). Because distinguishing individual lanthanides is analytically challenging, it is has been difficult to discern the effects of the individual lanthanides—both in human cases and animal studies. In addition, the co-occurrence of radioactive lanthanides, thorium isotopes, and silica dust has complicated the interpretation of toxicity—especially with regard to human exposures (Palmer et al., 1987, as cited by U.S. EPA, 2009b, 2009c, 2009d).

The pulmonary toxicity of inhaled REEs has been the subject of debate, especially with regard to the relative contributions of radioactive contaminants versus stable elements in the development of progressive pulmonary interstitial fibrosis (Haley, 1991; U.S. EPA, 2007b). In particular, although it is understood that stable REE compounds can produce a static, foreign-body-type lesion consistent with benign pneumoconiosis; it is uncertain whether they can also induce interstitial fibrosis that progresses after the termination of exposure. Human inhalation toxicity data on stable REEs mainly consist of case reports on workers exposed to multiple lanthanides (U.S. EPA, 2007b).

EPA has reviewed the human health toxicity for a few REEs in its Integrated Risk Information System (IRIS) and Provisional Peer-Reviewed Toxicity Values (PPRTV) programs. Human health benchmark values (where derived) and background toxicity information are summarized below (presented alphabetically by REE); the reader is referred to these health benchmark technical background documents for additional detailed information. EPA has not reviewed the toxicity of dysprosium, erbium, europium, holmium, lanthanum, scandium, terbium, thulium, ytterbium, or yttrium.

- **Cerium** – In a 2009 IRIS assessment on cerium oxide and cerium compounds, available human and animal studies demonstrated that ingested cerium may have an effect on cardiac tissue (endomyocardial fibrosis) and hemoglobin oxygen affinity; however, data were insufficient to derive an oral Reference Dose (RfD). An inhalation Reference Concentration (RfC) of 9E-4 mg/m^3 was derived based on increased incidence of alveolar epithelial hyperplasia in the lungs of rats. The lung and lymphoreticular system effects reported in the principal study are consistent with effects observed in humans, which were characterized by the accumulation of cerium particles in the lungs and lymphoreticular system and histologic effects throughout the lung. Data are unavailable regarding the carcinogenicity of cerium compounds in humans or experimental animals (U.S. EPA, 2011d).
- **Gadolinium** – In a 2007 PPRTV document, minimal effects on body weight gain and liver histology were reported following ingestion of gadolinium in rats. Pulmonary histopathological changes with manifestations that included decreased lung compliance and pneumonia leading to mortality were observed in mice and guinea pigs subchronically exposed to gadolinium oxide via

inhalation. Data were insufficient to derive any quantitative health benchmarks. Gadolinium was assigned a weight-of-evidence description of "inadequate information to assess carcinogenic potential" (U.S. EPA, 2007a).

- **Lutetium** – In a 2007 PPRTV document, a subchronic oral provisional RfD (p-RfD) of 9E-4 mg/kg/day was derived based on a stand-alone no observed adverse effect level (NOAEL) in mice; there are no data to indicate the toxicological endpoint(s) or target organ(s) of oral exposure to lutetium. A comprehensive assessment of human and animal data by Haley (1991) concluded that the evidence suggests that inhalation exposure to high concentrations of stable REEs can produce lesions compatible with pneumoconiosis and progressive pulmonary fibrosis, and that the potential for inducing these lesions is related to chemical type, physiochemical form, and dose and duration of exposure. Data were insufficient to derive an inhalation RfC. Lutetium was assigned a weight-of-evidence description of "inadequate information to assess carcinogenic potential" (U.S. EPA, 2007b).
- **Neodymium** –A subchronic oral p-RfD of 5E-1 mg/kg/day was derived for neodymium based on a freestanding NOAEL in rats (no effects on body weight, hematology, and histopathology) in a 2009 PPRTV document (subchronic p-RfD = 8E-1 mg $NdCl_3$/kg/day). Data were insufficient to derive an inhalation RfC. Neodymium was assigned a weight-of-evidence description of "inadequate information to assess carcinogenic potential" (U.S. EPA, 2009b).
- **Praseodymium** – In a 2009 PPRTV document, a subchronic oral p-RfD of 5E-1 mg/kg/day was derived for praseodymium based on a freestanding NOAEL in rats (no effects on body weight, hematology, and histopathology) (subchronic p-RfD = 8E-1 mg $PrCl_3$/kg/day). Data were insufficient to derive an inhalation RfC. Praseodymium was assigned a weight-of-evidence description of "inadequate information to assess carcinogenic potential" (U.S. EPA, 2009b).
- **Promethium** – Although a 2007 PPRTV document was prepared for promethium, no human health benchmarks were derived due to lack of data. Promethium was assigned a weight-of-evidence description of "inadequate information to assess carcinogenic potential" (U.S. EPA, 2007c).
- **Samarium** – In a 2009 PPRTV document, a subchronic oral p-RfD of 5E-1 mg/kg/day was derived for samarium chloride based on a freestanding NOAEL in rats (no effects on body weight, hematology, and histopathology) (subchronic p-RfD = 9E-1 mg $SmCl_3$/kg/day). A lowest observed adverse effect level (LOAEL) was reported for increased relative pancreas and lung weights and increased malondialdehyde concentrations in liver tissues of rats exposed to samarium nitrate in drinking water. Data suggest that different chemical forms of samarium have different toxic potencies. A subchronic study in samarium nitrate suggests a LOAEL point of departure more than 2000 times lower than the NOAEL point of departure for samarium chloride. In the absence of evidence explaining the large differences in apparent toxicity between the chloride and nitrate salts, the p-RfD for samarium chloride should be used with caution. The large differences in acute and subchronic toxicity preclude generalization of the p-RfD for samarium chloride to other samarium compounds. A screening subchronic oral p-RfD of 2E-5 mg/kg/day was also derived for samarium nitrate based on a freestanding NOAEL in rats (no effects on body weight, hematology, and histopathology) (screening subchronic p-RfD = 4E-5 mg $(SmNO_3)_3$/kg/day). Data were insufficient to derive an inhalation RfC. Samarium was assigned a weight-of-evidence description of "inadequate information to assess carcinogenic potential" (U.S. EPA, 2009d).

In addition to the EPA documents discussed above, Toxicology Excellence for Risk Assessment (TERA) (1999) conducted a literature review for the Bureau of Land Management (BLM) examining the health effects of lanthanides and developed non-radiological, non-cancer risk assessment values for the oral and/or inhalation routes of exposure. Human health benchmark values are summarized in **Table 6-3**, below.

Table 6-3. REEs and Available RfCs and RfDs

REE	Benchmark	Value	Source
Ceric oxide as Ce	RfC	3E-4 mg/cu.m	TERA, 1999
Cerium oxide as Ce	RfC	9E-4 mg/cu.m	U.S. EPA, 2011d
Europium chloride as Eu	RfD	3E-2 mg/kg-day	TERA, 1999
Europium oxide as Eu	RfD	2E-3 mg/kg-day	TERA, 1999
Gadolinium oxide as Gd	RfC	2E-3 mg/cu.m	TERA, 1999
Lanthanum carbonate as La	RfD	5E-1 mg/kg-day	NSF International, 2010
Lanthanum chloride as La	RfD	5E-3 mg/kg-day	TERA, 1999
Lanthanum oxide as La	RfD	2E-2 mg/kg-day	TERA, 1999
Lutetium chloride as Lu	s-RfD	9E-4 mg/kg-day	U.S. EPA, 2007b
Neodymium chloride as Nd	s-RfD	5E-1 mg/kg-day	U.S. EPA, 2009a
Praseodymium chloride as Pr	s-RfD	5E-1 mg/kg-day	U.S. EPA, 2009b
Samarium chloride as Sm	s-RfD	5E-1 mg/kg-day	U.S. EPA, 2009c
Samarium nitrate as Sm	s-RfD	2E-5 mg/kg-day	U.S. EPA, 2009c
Scandium oxide as Sc	RfD	5E-3 mg/kg-day	TERA, 1999
Yttrium chloride as Yt	RfD	4E-3 mg/kg-day	TERA, 1999

Additional primary toxicity studies were identified through the literature search and the objectives and key findings are briefly summarized in **Table 6-4**, below; the information is organized by REE.

Table 6-4. Selected Toxicity and Epidemiology Findings for Rare Earth Elements,

REE(s)	Citation	Objective/Purpose	Key Findings
Cerium	Gómez-Aracena et al., 2006. Toenail cerium levels and risk of a first acute myocardial infarction: The EURAMIC and heavy metals study. *Chemosphere 64*:112-120	Examine the association between cerium exposure and risk of first acute myocardial infarction (AMI) in a case-control study in Europe and Israel.	Cases had significantly higher levels of cerium than controls after various adjustments. Results suggest that cerium may possibly be associated with an increased risk of AMI.
Cerium	McDonald et al., 1995. Rare earth (cerium oxide) pneumoconiosis: analytical scanning electron microscopy and literature review. *Mod Pathol 8*:859-865	Describe a male patient's respiratory effects; patient had a chronic history of optical lens grinding, an occupation associated with exposure to cerium oxide.	Patient presented with progressive dyspnea and an interstitial pattern on chest X-ray; open lung biopsy showed interstitial fibrosis, while scanning electron microscopy demonstrated numerous particulate deposits in the lung (most containing cerium). This is one of the first cases to describe RE pneumoconiosis associated with pulmonary fibrosis in the occupational setting of optical lens manufacture.
Cerium, lanthanum, neodymium	Palmer et al.,1987. Cytotoxicity of the rare earth metals cerium, lanthanum, and neodymium in vitro: comparisons with cadmium in a pulmonary macrophage primary culture system. *Environ Res* 43:142-56.	Evaluate cerium, lanthanum, and neodymium in an in vitro cytotoxicity assay system using rat pulmonary alveolar macrophages. Both the soluble chloride form and their insoluble metal oxides were studied.	The results suggest that rare earth metal fumes should be considered as cytotoxic to lung tissue and potentially fibrogenic.

REE(s)	Citation	Objective/Purpose	Key Findings
Gadolinium	Bussi et al., 2007. Toxicological assessment of gadolinium release from contrast media. *Exp Toxicol Pathol 58*:323-330	In vivo gadolinium release was evaluated for 3 magnetic resonance imaging (MRI) contrast agents estimating gadolinium content in liver, kidneys, spleen, femur and brain after single or repeated intravenous administrations to rats. Gadolinium acetate (GdAc) was used as a positive control.	No blood chemistry, hematology, or histopathology changes were seen with the tested contrast media, whereas increased white blood cell count and serum cholesterol were found after GdAc.
Gadolinium	Perazella, 2009. Current status of gadolinium toxicity in patients with kidney disease. *Clin J Am Soc Nephrol 4*: 461-469.	Examine the possibility of nephrotoxicity from gadolinium-based contrast (GBC) in humans.	Reports of a rare systemic fibrosing condition called nephrogenic systemic fibrosis (NSF) were linked to exposure of patients with advanced kidney disease to certain GBC agents. Only patients with advanced acute or chronic kidney disease were found to be at risk for developing NSF.
Gadolinium	Sharma, 2010. Gadolinium toxicity: epidermis thickness measurement by magnetic resonance imaging at 500 MHz. *Skin Res Technol 16*: 339-353.	Assess the contrast agent gadolinium toxicity on mice skin by measuring regional epidermal thickening and hair follicle width resulting from delayed gadolinium contrast MRI.	Gadolinium treatment showed skin toxicity as epidermis thickening due to the use of high concentrations of gadolinium in microimaging.
Gadolinium, lanthanum	Yongxing et al., 2000. Genotoxicity of Lanthanum (III) and Gadolinium (III) in Human Peripheral Blood Lymphocytes. Bull Environ *Contam Toxicol 64*: 611-611.	Examine the genotoxicity of trivalent lanthanum and trivalent gadolinium in human peripheral blood.	Micronuclei frequency increased in a dose-dependent manner upon exposure to both rare-earth elements. Significant differences in single-stranded DNA breaks and unscheduled DNA synthesis.
Gadolinium, samarium	Haley et al., 1961. Toxicological and pharmacological effects of gadolinium and samarium chlorides. *Brit J Pharmacol* 17:526–532.	Examine the effects of $SmCl_3$ or $GdCl_3$ in food of rats for 12 weeks. Body weight, hematology, and histology were assessed.	Among Sm-treated animals, no exposure-related histopathological or other changes were observed. Minimally decreased body weight gain and liver histological alterations were reported in male, but not female, Gd-treated rats.
Holmium	Qiu et al., 2008. Current Research in Toxicology and Application of Rare-earth Element Holmium. *Huanjing yu Zhiye Yixue 25*:207-208	Review the potential cytotoxicity, genotoxicity, and biochemical toxicity of holmium.	NA

REE(s)	Citation	Objective/Purpose	Key Findings
Lanthanum	Damment et al., 2005. Evaluation of the potential genotoxicity of the phosphate binder lanthanum carbonate. *Mutagenesis 20*:29-37	Lanthanum was evaluated for potential genotoxicity using a range of in vitro assays (as the carbonate) in the presence and absence of post-mitochondrial fraction (S9) and in vivo in tests for mutagenicity and clastogenicity (as the carbonate and chloride).	The drug was devoid of mutagenic activity in bacterial assays (Salmonella typhimurium TA1535, TA1537, TA1538, TA98, TA100 and TA102 and Escherichia coli WP2 uvrA and WP2 uvrA pkm101). No effects were seen in the hgprt gene mutation assay in Chinese hamster ovary cells in the presence of S9. Authors concluded that lanthanum is not genotoxic.
Lanthanum	Feng et al., 2006. Neurotoxicological consequence of long-term exposure to lanthanum. *Toxicol Lett 165*:112-120	Study whether subchronic lanthanum [chloride] exposure affects nervous system function in rats.	Neurobehaviorial effects (as observed by Morris water maze test) were reported, as well as inhibited Ca(2+)-ATPase activity, disturbed central cholinergic system function, and decreased monoamines neurotransmitters. Chronic exposure to lanthanum may impair learning ability, possibly due to the disturbance of the homeostasis of trace elements, enzymes, and neurotransmitter systems in brain.
Lutetium	Haley et al., 1964a. Pharmacology and toxicology of lutetium chloride. *J Pharm Sci* 53:1186-1188.	Examine the effects of $LuCl_3$ in food of rats for 90 days. Body weight, hematology, and histology were assessed.	No exposure-related histopathological or other changes were observed.
Monazite	Katsnelson et al., 2009. Toxicity of monazite particulates and its attenuation with a complex of bio-protectors. *Med Lav 100*:455-470	Study the health effects of monazite particles in rats.	Intratracheal injection of monazite resulted in cytotoxicity, fibrogenicity, systemic toxicity, and genotoxicity.
Multiple	Bryan-Lluka and Bonisch 1997. Lanthanides inhibit the human noradrenaline, 5-hydroxytryptamine and dopamine transporters. Naunyn Schmiedebergs *Arch Pharmacol 355*:699-706	Determine the effects of lanthanides on the activities of the human noradrenaline, 5-hydroxytryptamine (5-HT), and dopamine transporters.	Lanthanides 1) cannot substitute for Na+ in the transport of substrates by monoamine neurotransmitter transporters and 2) inhibit the latter transporters by interacting with sites of the transporters involved in amine and Na+ binding.
Multiple	Fan et al., 2004. [Study on the effects of exposure to REEs and health-responses in children aged 7-10 years]. *Wei Sheng Yan Jiu 33*: 23-28	Study effects of environmental exposure to REEs on children's health.	Reported effects included significant differences in immunological parameters (IgM, CD3, CD4, CD4/CD8) , lower IQ scores, decreased percentage of high IQ, and increased percentage of low IQ.
Multiple	Haley. 1991. Pulmonary toxicity of stable and radioactive lanthanides. *Health Phys 61*:809-820	Examine whether lanthanide dusts that are devoid of radioactive contaminants are capable of producing progressive pulmonary disease, or are lanthanide-induced lesions more appropriately termed "benign pneumoconiosis".	Author reviews available epidemiological and animal data and concludes that the pulmonary syndrome induced by stable rare earths includes progressive pulmonary fibrosis and should not be referred to as "benign pneumoconiosis."

REE(s)	Citation	Objective/Purpose	Key Findings
Multiple	Hirano and Suzuki. 1996. Exposure, metabolism, and toxicity of rare earths and related compounds. Environ *Health Perspect 104 Suppl 1*: 85-95	Provide an overview of the metabolism and health hazards of REEs.	NA
Multiple	Ji and Cui 1988. Toxicological studies on safety of rare earths used in agriculture. *Biomed Environ Sci 1*:270-276.	Studied the toxicity of a mixture of rare earth metal nitrates (Ce, La, Nd, Pr, and Sm) used in agricultural operations.	In mice, rats, and guinea pigs, the oral LD50 ranged from 1397 to 1876 mg/kg; absorption in the gastrointestinal tract was low. Mild skin and eye irritation were reported in dermally exposed rabbits. No biochemical and histopathological effects were reported in monkeys or rats following subchronic exposure. No teratogenic effects were observed in rats. Ames mutagenicity tests were negative. The authors conclude that 60 mg/kg should be considered a NOAEL for the RE nitrate mixture, with an acceptable daily intake (ADI) of 0.6 mg/kg/day resulting.
Multiple	Palasz and Czekaj. 2000. Toxicological and cytophysiological aspects of lanthanides action. *Acta Biochim Pol 47*:1107-1114	Review the toxicological effects of several lanthanides.	Gadolinium selectively inhibits secretion by Kupffer cells and decreases cytochrome P450 activity in hepatocytes. Praseodymium ion produces the same effect in liver tissue cultures. Lanthanides' cytophysiological effects may result from the similarity of their cationic radii to the size of Ca2+ ions. Trivalent lanthanide ions, especially La3+ and Gd3+, block different calcium channels in human and animal cells. Lanthanides (Dy3+, La3+, Mg2+, Eu3+, Tb3+) can affect numerous enzymes. Lanthanide ions regulate the transport and release of synaptic transmitters and block some membrane receptors of neurons.
Multiple	Sabbioni et al., 1982. Long-term occupational risk of rare-earth pneumoconiosis. A case report as investigated by neutron activation analysis. *Sci Total Environ 26*: 19-32.	A case of rare-earth (RE) pneumoconiosis in a photoengraver is discussed.	Authors suggest that a relationship exists between pneumoconiosis and occupational exposure to RE dusts (La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu).
Multiple	Sarkander and Brade. 1976. On the mechanism of lanthanide-induced liver toxicity. *Arch Toxicol 36*: 1-17.	Examine the effects of Pr(III), Nd(III), Sm(III), Gd(III), Dy(III), and Er(III) on rat liver nuclear in vitro RNA synthesis catalyzed by RNA polymerase B.	The results indicate a primary ionic size-correlated interference of lanthanides with the nuclear control mechanisms of RNA synthesis.

REE(s)	Citation	Objective/Purpose	Key Findings
Multiple	Vocaturo et al., 1983. Human exposure to heavy metals. Rare earth pneumoconiosis in occupational workers. *Chest 83*: 780-783.	A case in a photoengraver is investigated with regard to potential RE pneumoconiosis.	Chest x-ray films showed a severe pulmonary fibrosis; high RE concentrations were reported in the pulmonary and lymph node biopsy specimens. Results suggest that long-term accumulation of RE in the lungs played a role in the pathogenesis of the observed pulmonary fibrosis of the worker.
Multiple	Wu et al., 2003. [A case-control study on the risk factors of leukemia in mining areas of rare-earth in South Jiangxi]. *Zhonghua Liu Xing Bing Xue Za Zhi 24*: 879-882.	Examine causes of leukemia in mining areas of REEs.	Leukemia was associated with environmental pollution with REEs and organophosphorus pesticides.
Multiple	Yu et al., 2007. Effects of REEs on telomerase activity and apoptosis of human peripheral blood mononuclear cells. *Biol Trace Elem Res 116*: 53-59.	Study effects of REEs on human telomerase and apoptosis of mononuclear cells from human peripheral blood (PBMNCs).	Increased telomerase activity and percentages of cells in the S-phase and the G2/M phase in PBMNCs, but no effect on the apoptotic rate of PBMNCs.
Multiple	Yu et al., 2004. [Effects of rare earth compounds on human peripheral mononuclear cell telomerase and apoptosis]. *Zhonghua Yu Fang Yi Xue Za Zhi 38*: 248-251.	Study effects of REEs on human telomerase and apoptosis of human peripheral mononuclear cells (PBMNs).	The telomerase activity of PBMNs was higher than controls, and there is no effect on apoptotic rate of PBMNs, but may promote the diploid DNA replication, and increase the percentage of G2/M and S phase cells.
Multiple	Zhang et al., 2000. Chronic toxicity of rare-earth elements on human beings: implications of blood biochemical indices in REE-high regions, South Jiangxi. *Biol Trace Elem Res 73*: 1-17.	Examine hematological parameters in humans with elevated REE exposures.	Decreased total serum protein (TSP), albumin, beta-globulin, glutamic pyruvic transitanase, serium triglycerides, and immunoglobulin, and increased cholesterol were reported.
Multiple	Zhu et al., 2005. Investigation on liver function among population in high background of rare earth area in South China. *Biol Trace Elem Res 104*: 1-8.	Investigate health effects of long-term ingestion of REEs on Chinese villagers living in high-REE-background areas.	Decreased serum total protein and globulin and albumin, and elevated IgM compared to controls.
Neodymium	Haley et al., 1964b. Pharmacology and toxicology of neodymium and neodymium chlorides. *Toxicol Appl Pharmacol* 6:614–620.	Examine the effects of $NdCl_3$ in food of rats for 90 days. Body weight, hematology, and histology were assessed.	No exposure-related histopathological or other changes were observed.
Neodymium, praseodymium	Haley et al., 1964c. Pharmacology and toxicology of praseodymium and neodymium chlorides. *Toxicol Appl Pharmacol 6*:614-620	Investigate pharmacology and toxicology of praseodymium and neodymium chlorides in animals.	Ingestion of $PrCl_3$ for 12 weeks produced no hematological or histopathological changes.

REE(s)	Citation	Objective/Purpose	Key Findings
Samarium	Weilin et al., 2006. Effects of samarium on liver and kidney of rats. *J Rare Earths* 24:415–418.	Study rats exposed to $Sm(NO_3)_3$ in drinking water for five months and examine for pathological changes.	Increased relative pancreas and lung weights and increased liver MDA concentrations were reported at the lowest dose.
Thulium	Fan et al., 2005. Effects of Thulium Exposure on IQ of Children. *J Environment and Health 22*:256-256-257	Study effects of environmental exposure to REEs on children's intelligence.	Significantly lower IQ score, decreased percentage of high IQ, and increased percentage of low IQ.

The literature review also identified biomonitoring studies in humans and plants, and are briefly summarized in **Table 6-5**. Information on REE concentrations in human hair and bone in regions of Chinese ore mining, as well as in tumors, was of particular interest. There is also a growing concern about the environmental impact of REE-enriched fertilizers, as they have been commonly used in agricultural settings in China since the 1980s. In spite of their increasing use, evidence of the effects of REE-enriched fertilizers on plant growth and crop yield is conflicting (positive, negative, and no effects have all been reported). A robust evaluation is not possible because access to the journal sources is difficult and most of the available research is only available in Chinese.

Table 6-5. Selected Biomonitoring Findings for Rare Earth Elements

REE(s)	Citation	Objective/Purpose	Key Findings
Cerium	Chua et al., 1998. Accumulation of Environmental Residues of Rare Earth Elements in Sugarcane. *Environ Int 24*: 287-287.	Leaves and roots of sugarcane and soil were exposed to radiolabeled Ce, and bioaccumulation in sugarcane was assessed.	Cerium was adsorbed in leaves via the stoma and cuticle and then rapidly distributed to various parts of the plant (roots, stems, leaves). Exposure to contaminated soil resulted in accumulation in the roots, bagasse, leaves, and sugarcane juice.
Cerium	Höllriegl et al., 2010. Measurement of cerium in human breast milk and blood samples. *J Trace Elements Med and Biol 24*:193-199.	The relationship between Ce content in human breast milk and blood plasma or serum was evaluated.	Cerium concentration in the breastmilk samples from Munich and Madrid showed low values. All (except 2) Ce concentrations in the German plasma samples were at the quantification limit, while the serum samples of the Spanish mothers showed cerium values ranging between 21.6 and 70.3 ng/L. The Ce content in plasma/serum (but not breastmilk) could possibly be an indicator for environmental Ce.
Dysprosium	Knaus and El-Fawaris. 1981. A biomonitor of trace heavy metals: indium and dysprosium in red alder roots (Alnus rubra Bong.). *Environmental and Experimental Botany 21*: 217-223.	Bioaccumulation of Dy by the roots of red alder (Alnus rubra Bong.) was tested in a small free-flowing stream in Oregon.	Non-chelated Dy was sorbed by roots up to a concentration of 29 µg Dy/g of root (dry wt), while the sorption of Dy-DTPA was less by a factor of 8.
Multiple	Koeberl and Bayer. 1992. Concentrations of REEs in human brain tissue and kidney stones determined by neutron activation analysis. *J Alloys and Compounds 180*: 63-70.	Measured REE concentrations in freeze-dried human brain tissue and in kidney stones.	Concentrations for 9 REEs (La, Ce, Nd, Sm, Eu, Gd, Tb, Dy, Yb, Lu) were reported. A difference between the REE patterns for apatite and oxalate kidney stones was observed.

REE(s)	Citation	Objective/Purpose	Key Findings
Multiple	Liang et al., 2005. Environmental biogeochemical behaviors of REEs in soil-plant systems. *Environmental Geochemistry and Health 27*: 301-311.	REEs' content in soil and various parts of wheat under different conditions in soil-plant systems were measured by INAA and ICP-MS.	The mean value of total REEs in soil of China was 176.8 mg/kg. The mean ratio of SigmaLREE/SigmaHREE in soils was 8.0 and cerium accounts for 42% of the total REEs. The content of REEs in wheat seed ranged between 10E-11 and 10E-8 g/g, 3-4 orders of magnitude lower than that in soil. The REEs contents in ryegrass, especially in roots, were significantly related to that of soil. The bioavailability of REEs in soil mainly depended on the exchangeable fraction of REEs, which was strongly affected by the physico-chemical properties of the soil. At the maturing stage of spring wheat, the REEs content was in the order of root > leaf >stem and crust.
Multiple	Lihong et al., 1999. The effect of EDTA on REEs bioavailability in soil ecosystem. *Chemosphere 38*: 2825-33.	The effects of EDTA on the bioaccumulation of REEs by wheat seedlings growing in two types of soils were studied.	The bioaccumulation values of REEs in wheat roots were much higher than those in the tops (stems and leaves) for both types of soils. EDTA promoted REEs bioavailability of wheat by increasing the REEs desorption from soils.
Multiple	Linsalata et al., 1985. "Determination of the Human Intake of Thorium and the Light Rare Earth Elements from High and Typical Natural Radiation Environments." Univ of Missouri/et al Trace Subst in Environ Health 19th Conf, Columbia: 257-257.	Measure the human ingestion of thorium and light REEs in Minas Gerais, Brazil, at a location near an ore body containing > 100,000 metric tons of REE.	Based on measurement in feces of residents located near the ore body, the annual ingestion intakes of Ce, La, Th, and Sm calculated from median concentrations are 24, 10, 5, and 0.6 mg/yr, respectively, for residents of one farm, and 42, 15, 3, and 1 mg/yr, respectively, for residents of the second farm. Comparable ingestion rates for residents of NY are 2.9, 1, 0.2, and 0.1 mg/yr, respectively.
Multiple	Peng et al., 2003. [Relationship of the hair content of REEs in young children aged 0 to 3 years to that in their mothers living in a rare earth mining area of Jiangxi]. *Zhonghua Yu Fang Yi Xue Za Zhi 37*: 20-22.	To study the relationship of hair content of REEs (La, Ce, Pr, Nd, Sm) in young children (aged 0 - 3 years) to that in their mothers living in a rare earth mining area of Jiangxi Province.	The mean hair content of REEs (e.g., La) was the highest (2,202.9 ng/g) in the young children living in the place nearest to the REE mining area, next was in those near the low-exposure area, and the lowest was in those in the control area. Pair-comparison analysis for the means showed that the average hair level of five kinds of REEs in the young children was two times high as their mothers'. The hair level of REEs can be used as a biomarker to reflect body's level of exposure to REEs. The hair level of REEs in young children and their mothers decreased with the increase of the distance from their home to rare earth mining area. Young children living in the area with REEs mining may be the high-exposure population.

REE(s)	Citation	Objective/Purpose	Key Findings
Multiple	Tong et al., 2004. Distribution characteristics of REEs in children's scalp hair from a rare earths mining area in southern China. *J Environ Sci Health A Tox Hazard Subst Environ Eng 39*(9): 2517-2532.	Validate the use of REE scalp hair content (La, Ce, Pr, Nd, Sm) as a biomarker of exposure. Hair content data were collected on 16 REEs from children aged 11-15 years old and living in an LREEs mining and surrounding areas in southern China.	REEs hair content from the mining area (e.g., range: La: 0.14-6.93 µg/g; Nd: 0.09-5.27 µg/g; Gd: 12.2-645.6 ng/g; Lu: 0.2-13.3 ng/g; Y: 0.03-1.27 µg/g; Sc: 0.05-0.30 µg/g) were significantly higher than those from the reference area and higher than those previously published.
Multiple	Zaichick et al., 2011. Accumulation of REEs in human bone within the lifespan. *Metallomics 3*: 186-194.	The concentrations of REEs (Ce, Dy, Er, Gd, La, Nd, Pr, Sm, Tb, Yb, Ho, Lu, Tm, Y) in the rib bone tissue of healthy humans (38 females and 42 males, age 15 to 55 years old) were determined using ICP-MS.	Age-related accumulation of REEs were found in the bone tissue of healthy individuals who lived in a non-industrial region.
Multiple	Zhang et al., 2003. [Levels and distribution of 15 REEs in tumor and normal lung tissue from the patients with lung cancer]. *Wei Sheng Yan Jiu 32*: 423-426.	Tumor tissue and normal tissue around tumors were collected from patients with lung cancer and 15 REEs were measured by ICP-MS.	Levels of 15 REEs in normal tissues around the tumor was as 2.07-2.51 times high as those in the tumor tissue. Contents of light REE in lung tissue of health human were higher while the contents of media and heavy REE were lower.
Multiple	Zhuang et al., 1996. Concentration of REEs, As, and Th in human brain and brain tumors, determined by neutron activation analysis. *Biol Trace Elem Res 53*: 45-49.	6 REE concentrations of brain tumor tissues from 16 patients with astrocytomas (grade I-III) and normal human brain tissues of 18 male, age-matched autopsies serving as controls were measured.	Concentrations of Th, La, Ce, Gd, and Lu were significantly higher in tumor tissues.

The literature review also identified ecological studies, which are summarized in **Table 6-6**, below. Information on ecological effects of REE on marine organisms, soil fauna, and plants were of particular interest. Many studies were conducted by Chinese researchers. It should be noted that this literature search was limited to the ecological effects of REEs, rather than the broader environmental contamination impacts resulting from REE extraction, processing, waste management, and industrial practices.

Table 6-6. Selected Ecotoxicity Findings for Rare Earth Elements

REE(s)	Citation	Objective/Purpose	Key Findings
Cerium, lanthanum	Oral et al., 2010. Cytogenetic and developmental toxicity of cerium and lanthanum to sea urchin embryos. *Chemosphere 81*: 194-198.	Evaluate the toxicity of Ce and La on sea urchin (*Paracentrotus lividus*) embryos and sperm.	Embryos reared in 10(-5)M Ce resulted in 100% embryonic mortality, whereas 10(-5)M La induced 100% developmental defects, without causing any embryonic mortality. A significant concentration-related mitotoxic effect and induction of mitotic aberrations were observed in Ce-exposed, but not in La-exposed embryos, at concentrations ranging from 10(-7)M to 3 x 10(-6)M. Following sperm exposure, both Ce and La induced a decrease in sperm fertilization success at the highest tested concentration (10E-5 M). The offspring of Ce-exposed, but not of La-exposed sperm displayed a significant concentration-related increase in developmental defects.
Gadolinium	Saitoh et al., 2010. Asymmetric inhibition of spicule formation in sea urchin embryos with low concentrations of gadolinium ion. *Dev Growth Differ 52*(9): 735-746.	Study the effects of gadolinium ion, a Ca(2+) channel blocker, on spicule formation in sea urchins.	Gd(3+) exerts an inhibitory effect on spicule formation through a mechanism that does not involve inhibition of Ca(2+) channels.
Holmium	Qu et al., 2004. [Research on the cytotoxic and genotoxic effects of rare-earth element holmium to Vicia faba]. *Yi chuan = Hereditas / Zhongguo yi chuan xue hui bian ji 26*(2): 195-201.	The root tips of Vicia faba were soaked in a holmium solution for 6hr and then cultivated for 22-24 hr. The frequency of micronucleus (FMN), the frequency of chromosomal aberrations (CAF), and mitosis index (MI) were calculated.	Holmium demonstrated certain cytotoxic and genotoxic effects.
Lanthanum	Barry and Meehan. 2000. The acute and chronic toxicity of lanthanum to Daphnia carinata. *Chemosphere 41*: 1669-1674.	Acute and chronic toxicity of lanthanum to Daphnia carinata.	La was most toxic to Daphnia in soft tap water (acute 48-h EC50 = 43 µg/l) compared to ASTM hard water (ASTM) (EC50 = 1180 µg/l). In the third growth medium, diluted sea water (DW) (EC50=49 µg/l), there was significant precipitation of La. There was 100% mortality at concentrations ≥ 80 µg/l by day six using DW media, but no effect on survival growth or reproduction at lower concentrations. In the ASTM media, La caused significant mortality to Daphnia at concentrations ≥ 39 µg/l, however, at least one animal survived to the end of the study at each of the tested concentrations. There was no effect of La on growth of surviving daphnids at concentrations ≤ 57 µg/l, however, second brood clutch sizes were significantly increased. La also caused delayed maturation.

REE(s)	Citation	Objective/Purpose	Key Findings
Lanthanum	Chu et al., 2003. Availability and toxicity of exogenous lanthanum in a haplic acrisols. *Geoderma 115*(1-2): 121-128.	Study the availability and toxicity of exogenous La in Chinese soil. The toxicity of La was determined by the evaluation of relative luminosity of Photobacterium phosphoreum T3.	The exogenous La was highly available in soil, and the average available La accounted for 56.6% of exogenous La after 1 week of incubation. La was biologically toxic in aqueous solution and soil. Results indicate that the excessive exogenous La in soil may harm soil microbial community.
Lanthanum	Zhang et al., 2010. Ecotoxicological assessment of lanthanum with Caenorhabditis elegans in liquid medium. *Metallomics 2*: 806-810.	Caenorhabditis elegans was used as a test organism to evaluate the aquatic toxicity of La.	La(3)+ had significant adverse effects on the growth and reproduction of worms above a concentration of 10 μmol/L. La treatment disturbed the metals distribution in the whole body of a single tiny nematode at lower levels.
Lanthanum	Zhao et al., 2005. The effect of the rare earth La2O3 on growth and reproduction of Tenebrio molitor. *Chinese Bulletin of Entomology* 42: 444-449.	The effects of the rare earth La_2O_3 on growth and reproduction of Tenebrio molitor L. were studied. Newly eclosion larvae and adults were continuously reared in the La_2O_3 food (contaminated wheat bran) with different dosages.	After 79 d the larvae reared on the food with 40 mg La/kg gained 43% more weight and the female lay 59% more eggs daily in peak oviposition period than the control group. The larvae fed on the food with the dosage of 40 mg La/kg for 50 d resulted in 0.4% La accumulated in the larval body.
Multiple	Chen et al., 2000. Effects of Rare Earth Metal Ions and Their EDTA Complexes on Antioxidant Enzymes of Fish Liver. *Bulletin of Environmental Contamination and Toxicology 65*(3): 357-365.	Study toxicological effects of different species of REE to goldfish and validate the potential use of antioxidant enzymes as early biomarkers of REEs in aquatic ecosystem.	The exposure tests were performed to observe the changes of SOD CAT activities of goldfish with the control at selected times. The toxicological effects on goldfish were estimated with contrast and analysis of the test data.
Multiple	He and Xue. 2005. [Biological effects of REEs and their action mechanisms]. *Ying Yong Sheng Tai Xue Bao 16*: 1983-1989.	Review the effects of REEs on plant root development, biomass, quality, and resistance against stress.	REEs can enhance chlorophyll content, improve photosynthetic rate, increase plant biomass, promote uptake and utilization of nutrients by plant when appropriate amount of REEs was applied.
Multiple	Ippolito et al., 2010. Responses of antioxidant systems after exposition to rare earths and their role in chilling stress in common duckweed (Lemna minor L.): a defensive weapon or a boomerang? *Arch Environ Contam Toxicol 58*: 42-52.	Study the effects of a mix of different REE nitrate and lanthanum nitrate on catalase and antioxidant systems involved in the ascorbate-glutathione cycle in common duckweed Lemna minor L.	L. minor shows an overall good tolerance to the presence of REEs in the media. Treatments (up to 5 mM REE and 5 mM La) did not cause either visible symptoms on plants or significant effects on reactive oxygen species production, chlorophyll content, and lipid peroxidation. Toxic effects were observed after 5 days of exposure to 10 mM REE and 10 mM La.
Multiple	Li et al., 2006. [Effects of REEs on soil fauna community structure and their ecotoxicity to Holotrichia parallela]. *Ying Yong Sheng Tai Xue Bao 17*: 159-162.	Study the effects of applied REEs on soil fauna community structure and their ecological toxicity to Holotrichia parallela in bean field.	No significant differences between the treatments and the control were observed in soil fauna species, quantity of main species, and diversity index.

REE(s)	Citation	Objective/Purpose	Key Findings
Multiple	Tai et al., 2010. Biological toxicity of lanthanide elements on algae. *Chemosphere 80*: 1031-1035.	Study the biological toxicity of REEs on marine monocellular algae (Skeletonema costatum).	All single lanthanides had similar toxic effects on Skeletonema costatum. High concentrations of lanthanides (29.04 µmol/L) resulted in 50% reduction in growth of algae compared to controls (96 hr-EC50). A mixed solution that contained equivalent concentrations of each lanthanide element had the same inhibition effect on algae cells as each individual lanthanide element at the same total concentration. The authors conclude that the monocellular organisms might not be able to sufficiently differentiate between the almost chemically identical lanthanide elements.
Multiple	Tang et al., 2004. [Ecological effects of low dosage mixed REEs accumulation on major soil microbial groups in a yellow cinnamon soil]. *Ying Yong Sheng Tai Xue Bao 15*(11): 2137-2141.	The ecological effects of low dosage of mixed REE accumulation on major soil microbial groups in a yellow cinnamon soil was studied.	The continuous accumulation of REE had the alternative effects of stimulation, inhibition, and re-stimulation on soil bacteria and actinomycetes, and a continuous stimulation on soil fungi. At the accumulation of 150 mg/kg of REE, the population structure of three groups changed remarkably. The number of REE-tolerant microbes increased, with gram negative bacteria, white spore group and penicillium being predominant in bacteria, actinomycetes and fungi population, respectively. The authors propose an EC50 value of 30 mg/kg for the critical value of mixed REE in yellow cinnamon soil.
Multiple	Xie. 2007. Detection of Genotoxicity of 6 Kinds of Rare Earth Nitrates Using Orthogonal Experimental Design. *J Agro-Environment Science 26*: 150-155.	The genotoxicity of 6 kinds of RE nitrates ($Ce(NO_3)_3$, $Er(NO_3)_3$, $Sm(NO_3)_3$, $La(NO_3)_3$, $Y(NO_3)_3$, $Eu(NO_3)_3$) to root tip cells of maize was detected using micronucleus test.	5 RE nitrates played a role in the formation of micronuclei in root-tip cells of maize, while La nitrate had no significant influences. With the concentration increasing, the FMN in root-tip cells of maize treated by RE compounds increased significantly compared with the control group. Combined toxic effect was also observed. The 6 RE nitrates had genotoxicity to root tip cells of maize and showed no interaction with each other.
Terbium	Liu and Zhou. 2007. Response of Terbium Ecotoxicity Effect on Cochlearia armoracia L. Peroxidase (HRP) to Light. *J Agro-Environment Science 26*: 977-979.	Study the ecotoxicity effects of terbium on Cochlearia armoracia L. peroxidase (HRP) at different lights.	The results indicate the toxic effect of Tb(III) on HRP was increased with strong light.

REE(s)	Citation	Objective/Purpose	Key Findings
Terbium	Peng et al., 2007. Ecotoxicity of Terbium to Peroxidase Activity of Cochlearia armoracia L. Under Different Light and Temperature. *J Agro-Environment Science 26*: 974-976.	Study the ecotoxicity effects of terbium on Cochlearia armoracia L. peroxidase (HRP) at different temperatures.	The results indicate the toxic effect of Tb(III) on HRP was increased with high temperature.
Ytterbium	Hongyan et al., 2002. Physiological Responses of Carassius auratus to Ytterbium exposure. *Ecotoxicology and Environmental Safety 53*: 312-316.	Physiological and biochemical effects to the liver of Carassius auratus were investigated in vivo following 40 days of exposure to ytterbium.	Glutamate-pyruvate transaminase (GPT), superoxide dismutase (SOD), catalase (CAT), glutathione S-transferase (GST), and glutathione peroxidase (GSH-Px) activities were affected in goldfish liver. CAT was most sensitive to Yb3+, indicating that CAT might be a potential tool in the biomonitoring of exposure to Yb3+ in an aquatic ecosystem.

7. Summary, Key Findings from Literature Review, and Potential Next Steps

The purpose of this report is to serve as a technical information resource to policy makers and other stakeholders who are concerned with the potential environmental and health effects and impacts that can be identified across the REE supply chain. RTI conducted a search of the technical literature and other Internet sources related to each segment of the supply chain, including recent initiatives of U.S. government agencies that document issues associated with REE production, processing, manufacturing, end uses, recycling, and health/ecological effects. Information contained in this report also draws upon past domestic and international experience, as appropriate. The vast majority of information in this report is current. But, as noted in this report, mining and extraction of REEs is dynamic. Therefore, some details regarding who is producing what and where may have changed between the time when: (1) data collection as part of the literature search for this report was complete in July 2011, (2) the report's contract was completed in September 2011, and (3) its subsequent publication in 2012.
Although the current literature provides limited information specifically relating to REE mining, processing, recycling, and environmental or health impacts, it is expected that more information will be produced in the future as a result of the increased level of interest in REEs in the past few years.

7.1 Summary

REEs include the series of 15 lanthanide metals, plus scandium and yttrium. REEs have become increasingly important in recent years because their unique chemical and physical properties have contributed to technological advances in many areas, such as wind turbines, hybrid electric vehicles, energy-efficient lighting, computers and electronics, and defense applications such as lasers.

In 1984, the Molycorp Minerals, Inc. mine in Mountain Pass, CA, supplied 100 percent of U.S. demand and 33 percent of the world's demand for rare earths. The mine was shut down in 2002 for a variety of reasons, and since that time, China has become the world's leading producer of REEs, handling approximately 95 percent of worldwide production. Due to the increase in demand and the reduction in supply of REEs, the cost of REEs has increased dramatically in recent years. Given the strategic importance, supply concerns, and increasing cost of REEs, REE mines outside China are currently being evaluated or are in development, including multiple sites in the United States. Past producers of rare earths are re-opening idle or closed mines, and active mines that produce other metals that usually send rare earths as waste are now considering recovery of rare earth oxides.

Molycorp Minerals, Inc. is at the forefront as one of the first companies to reinitiate mining operations at their existing Mountain Pass mine. Molycorp also is attempting to find better mineral processing methods that allow recovery of more rare earth oxides from the ore at a lower cost and with less environmental impact.

Outside of direct mining operations, other sources of rare earths are being explored, such as recovery from recycling or urban mining. Currently, commercial recycling of rare earths is very limited; however, it is reported in the literature that, within the next year, several new commercial recycling operations will begin operation, with the focus being on magnets, batteries, lighting and luminescence, and catalysts.

Mining and processing activities have the potential to create a number of environmental risks to human health and the environment. The severity of these risks is highly variable between mine and mine plant operations. The contaminants of concern will vary depending on the REE-mineral ore, the toxicity of the contaminants from the waste rock, ore stockpiles, and process waste streams. The mobility of contaminants will be controlled by the characteristics of the geologic, hydrologic, and hydrogeologic

environments where the mine is located, along with the characteristics of the mining process and waste handling methods.

The results from the preliminary literature search related to human health, epidemiology, toxicity, biomonitoring, and ecological studies on REEs resulted in limited data. Most of the studies identified in the literature review examined mixtures of REEs, rather than individual elements. In addition, many studies were conducted in regions of Chinese ore mining by Chinese investigators and were not available in English (only the abstracts were available in English).

7.2 Key Findings

As mentioned previously, this report summarizes the information available during this report's production and review and should be considered a starting point for future investigations related to the potential environmental and health issues concerning the production, processing, recycling, recovery, and life cycles of REEs. Key findings from this literature review include the following:

- Analysis of the future supply and demand for each of the REEs indicates that, by 2014, global demand could exceed 200,000 tons per year, which would exceed current production by over 75,000 tons per year. It is reported that if the new mines under development are able to meet their projected production levels, world-wide demand for REEs will be met from these new sources.
- The waste footprint and environmental impacts from mining operations to extract rare earth mineral ores are expected to be as significant as current metals/minerals mining practices. The environmental effects on local communities and habitats must be determined so that mitigation measures can be considered when determining the feasibility of a proposed rare earth mining project. Planning the mine in advance and planning for waste management associated with long-term projects is important to the successful future restoration of a mine site.
- The most significant environmental impact from contaminant sources associated with hardrock mining is to surface water and ground water quality. However, documented impacts also have occurred to sediments, soils, and air. Mining for rare earth mineral ores and processing those ores into the final products can be compared to other hardrock metal mining and processing operations, and similar environmental impacts and risks would be expected.
- AMD usually is not a significant issue for REE deposits; however, the rock that surrounds or is overlying an ore body may contain the sulfide minerals that could create AMD. REEs often occur in ores rich in carbonate minerals, which generally have high acid-neutralizing potential and therefore, can help buffer any effects of acidic mine drainage that might occur.
- Rare earth milling and processing is a complex, ore-specific operation that has potential for environmental contamination when not controlled and managed appropriately. Waste streams with the greatest pollution potential are the tailings and their associated treatment and storage. Heavy metals and radionuclides associated with REE tailings pose the greatest threat to human health and the environment when not controlled. However, adoption of new technologies and management processes has the potential to reduce the risk of environmental contamination.
- Increased demand and reduced supply of REEs, along with the knowledge of the quantities available in waste products, has resulted in expanded research and development efforts focused on the recycling of, and identification of alternatives to, rare earths. Currently, commercial recycling of rare earths is very limited; however, it was reported in the literature that within the next year several new commercial REE recycling operations will begin operation.
- Another potential source of REO is the tailings waste from other mineral processing operations. For example, the apatite tailings from the Pea Ridge iron ore mine and processing operation contain 0.5% REO. The tailings impoundment currently contains 20 million tons.

- While environmental impacts can occur, when compared with primary processing of metals, it is reported that controlled recycling of REEs will provide significant benefits with respect to air emissions, groundwater protection, acidification, eutrophication, and climate protection.
- Frequently, recycling of electronics is taking place outside of the United States in developing countries using informal processes. These informal operations can include manual dismantling, open burning to recover metals, de-soldering of printed wiring boards over coal fires, and acid leaching in open vessels—all with the potential for significant, adverse environmental and human health impacts.
- The specific health effects of elevated concentrations of REEs in the environment from mining and processing REE-containing ores are not well understood. From the limited literature review, it appears that most available epidemiological data are for mixtures of REEs rather than individual elements. These data indicate that pulmonary toxicity of REEs in humans may be a concern. Additionally, as referenced in Section 6, the larger, lighter (i.e., smaller atomic number), and less soluble ions have been observed to deposit primarily in the liver, while the smaller, heavier (i.e., larger atomic number), and more soluble ions are similar in ionic radius to divalent calcium and distribute primarily to bone.

7.3 Suggested Next Steps

Suggested next steps that could provide the additional information necessary to fill current knowledge gaps and support future decision-making efforts include the following:

1. Conduct technology review(s) of wastewater treatment (including an evaluation of the environmental impacts) for REE mining and processing operations. Following the technology review, efforts could focus on technology development to address gaps identified in the review.
2. Conduct sustainability studies focused on urban mining in the United States to include information on REEs (and other high-value materials) contained in products, the value of those materials, methods for reclaiming or recycling the materials, and the environmental impacts from all steps. Such studies could take a life-cycle approach and include topics such as design of products to make recycling easier.
3. Support research focused on determining the technical and economic barriers to recycling of certain rare earths. Following determination of the barriers, explore options for reducing/eliminating the barriers, including technology research, development, and environmental impact studies.
4. Expand upon the information provided in this report and develop a system understanding for all elements associated with REE mining, processing, and recycling that have the potential for environmental or health impacts. Use this information to perform regional environmental evaluations of locations where REE mines, processing facilities, and recyclers are likely to be developed to determine the potential for environmental and health impacts that could occur. Use the results to plan and prioritize research, regional technical support, and regulatory efforts.
5. Conduct a more complete review of the health, biomonitoring, and ecological impacts literature—to include a comparison of the references cited in health background documents to the preliminary literature search results presented in this document—to ensure all available studies are included.
6. Support additional human health toxicity and ecological impact studies on specific REEs and then use this information to conduct risk assessments related to REE mining, processing, and recycling.

7. Convene EPA/federal agencies/industry workshops and information exchanges on topics related to REE technology development, recycling, and impacts.
8. Engage other federal agencies, such as DOE, DOD, DOI, USGS, and the BLM, in the coordination of research, technical support, outreach, policy, and regulatory efforts in the REE arena.
9. Develop outreach and decision support tools, such as guidance documents, decision trees, and websites, to provide technical support and information exchange to EPA Regions, states, and other interested parties.

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Appendix A

Selected Chemical Properties of REEs

It was once thought that rare earth elements (REEs) naturally occur as oxides, referred to as "earths," but it is now understood that these elements do not naturally occur in the form of an oxide in natural deposits. Commonly, modern geochemists refer to REEs as the "lanthanide group elements," or "lanthanides," since lanthanide is positioned first in a series of elements that all share similar chemical properties. The elements scandium and yttrium have almost identical physical and chemical properties to that of the lanthanide group elements; therefore, these are also included in the lanthanide group. All the rare earths except promethium (Pm) are available in nature. Promethium occurs by thermal neutron fission of uranium (U^{235}) or by bombarding neodymium with neutrons produced from uranium fission in a nuclear reactor.

The natural geochemistry and physico-chemical properties of REES that control background concentrations of these metals in the environment are not well understood, nor are the factors influencing bioavailability. Studies in the literature appear limited at the present time. Measurement of rare earth metals (REMs) in environmental media is also problematic due to the physico-chemical properties that make them unique. Predicting the environmental human and ecological health risks associated with anthropogenic activities that have the potential to release REMs to the environment is difficult and not straightforward. Some of the physico-chemical characteristics of lanthanides are presented below that likely affect the occurrence and bioavailability of these metals. Although not included here, an extensive tabulation of the properties for the lanthanide group metals is provide by Gupta and Krishnamurthy (2004) and others.

In general, metals typically exist in the environment in several different forms, depending on ambient chemical conditions (e.g., pH, organic carbon, presence of other chemicals). The chemical form of a metal, or its speciation, can play a large role in its fate and bioavailability and, thus, in its potential to produce toxic effects (Langmuir et al., 2004). Because of the high variability in both biotic and abiotic factors (e.g., pH) affecting the speciation and bioavailability of metals within and between environmental media, risks posed by metals often can vary by orders of magnitude depending on the speciation. Environmental conditions can change significantly, even over small spatial scales (e.g., a few centimeters in a sediment transitioning from an aerobic zone downward to an anaerobic zone), and such significant shifts in conditions can lead to significant changes in metals speciation and risk. Evidence found pertaining to the toxicity and health effects of lanthanides is provided in ***Section 6*** of the main document to this appendix.

The rare earths are so chemically similar to one another that separation of individual elements from the host minerals is difficult (see Section 4). Their similarity is also demonstrated by their occurrence together in the same geological deposits; however, that does not imply that these metals respond equally to changes in natural systems (Weber, 2008). It is believed that the lanthanide group elements also have very similar electronic configurations; however, due to the complexity of the electron spectra and difficulty of analysis the electron configuration is not known with complete certainty (Gupta and Krishnamurthy, 2004).

There are observed distributions for lanthanide group elements in the natural environment indicating that they will, under the right conditions, separate from the each other. Preferences for the occurrence of certain lanthanides have been observed in different mineral types. In aqueous solution, separation also occurs due to variable stability constants, indicating the strength of the chemical bond of lanthanide-ligand complexes (Weber, 2008). Observations like these have suggested a subdivision of the lanthanides

into various groupings as presented by Gupta and Krishnamurthy (2004) from other sources and that are presented below. Previously the lanthanides were categorized into three groups according to Kramers in 1961:

- Light (or cerium) lanthanide group – lanthanum (La) through samarium (Sm);
- Middle (or terbium) lanthanide group – europium (Eu) through dysprosium (Dy);
- Heavy (or yttrium) lanthanide group – holmium (Ho) through lutetium (Lu) and including yttrium.

More recently, two other attempts have been made to subdivide the lanthanides into groups:

(after Jackson and Christiansen, 1993):

- Light (or cerium) lanthanide group – lanthanum (La) through gadolinium (Gd); and
- Heavy (or yttrium) lanthanide subgroup – terbium (Tb) through lutetium (Lu), including yttrium.

(after Sabot and Maestro, 1995)

- Light lanthanide group – lanthanum (La) through neodymium (Nd);
- Middle lanthanide group – samarium (Sm) through dysprosium (Dy);
- Heavy lanthanide group – holmium (Ho) through lutetium (Lu) and including yttrium.

Other groupings continue to be developed based on newer studies and observations and according to purpose.

The chemical properties of metals are determined by the valence electrons or the number of bonds that can be formed by an atom. Rare earths differ from other metals since their valence electrons are not located in the outermost shell of the atom, rather the valence electrons of the lanthanide group are positioned in the (4f) subshell that is shielded by two larger closed (or full) subshells (5s2 and 5p6). Regardless of the attempted groupings, this atomic configuration supporting stable outermost electron shells results in the very similar chemical properties of the lanthanide group in general and the difficulty in their separation during processing.

Contrary to the general trend in the periodic table, it has been observed in the lanthanide group that the atomic radii of the elements and their ions decrease slightly as the atomic numbers increase (starting with cerium). Lanthanum has the largest radius and lutetium the smallest, owing to the incremental increase of 4f orbital electrons by one across the group. In very general terms, a current theory considers that the atomic nucleus of the lanthanide elements is poorly shielded, and therefore with the increase in atomic number, the nuclear charge experienced by the 4f orbital electrons increases as well. The effect of this shielding pattern results in a contraction of the 4f shell as that subshell's electrons are pulled closer to the nucleus. This reduction in ionic radii across the lanthanides with increasing ionic charge is referred to as the "lanthanide contraction." The difference in ionic radius of adjacent rare earths is very small. For example, the ionic radius of Ce^{+3} is 1.06 Å and that of Lu^{+3} is 0.85 Å. The lanthanide contraction controls many of the features observed for REE chemistry. The chemistry of lanthanides is predominantly ionic and is determined primarily by the size of the trivalent ion.

All the REMs typically occur in the trivalent (M^{3+}) state in terrestrial environments. However, a few of the REMs occur in other ionic forms such as samarium (Sm^{2+}), thulium (Tm^{2+}), and ytterbium (Yb^{2+}), but only the alternate forms of cerium (cerous, Ce^{4+}), and Europium (Eu^{2+}), are commonly found in natural systems (Railsback, 2008). Since the outer orbitals of lanthanides have higher energy, they tend not to form covalent bonds (Weber, 2008). Some covalency is exhibited and increases slightly with increasing

atomic number; however, bonding is predominantly ionic, even with extra electrons in the d-orbitals of some lanthanides.

An important chemical property is that the lanthanides will form strong complexes with a number of different ligands. Water is a strong ligand for trivalent (M^{3+}) lanthanides (Weber, 2008). Trivalent (M^{3+}) lanthanides strong affinity for water allows them to form a hydration shell around the Ln^{3+} ion. The number of molecules of water that a lanthanide ion can bond with in an aqueous solution varies between 8 and 9, depending on the element and species (Weber, 2008). Weber (2008) points out that the basic physico-chemical properties of lanthanides in natural aqueous systems (e.g., interstitial soil water in the unsaturated zone) depend significantly on the presence of other coordinating compounds that can displace the water molecules from around the lanthanide metal ion.

In aqueous environments, the water ligand would only be displaced if ligands with small ionic radius were present with a high oxidation state, high electronegativity, and with the highest occupied molecular orbitals having low energy; examples of these chemical species are the hydroxyl anion (OH^-), fluorine (F^-), chlorine (Cl^-), ammonia (NH^3), acetic acid (CH^3COO^-), carbonic acid (CO_3^{2-}), nitrate (NO^{3-}), sulfate (SO_4^{2-}), phosphate (PO_4^{3-}), oxide (O^{2-}), alcohols (R –OH), amines (R-NH_2), and others containing highly electronegative donor atoms such as O and F. These chemical species would tend to form mainly an ionic bond with the lanthanides molecules within their unoccupied lower high-energy orbitals. Lanthanides preferentially bond with oxygen atoms in aqueous solutions, but one-to-one bonding between lanthanides and other compatible ions has been shown to be weak compared to bonding with oxygen or flourine atoms and easily hydrolyzed by water (Gupta and Krishnamurthy, 2004; Weber, 2008). However, polydentate ligands, which have multiple pairs of electrons that can bond to the lanthanide metal ion, will form stronger bonds that may be more stable in aquatic environments. In general, the lanthanide ion preference for donor atoms is O>N>S (Weber, 2008).

At ambient temperatures, all REMs are not affected by air the same way. The ionization energies (or strength of the nuclear charge) of lanthanides are comparatively low, meaning it takes less energy to remove valence electrons. These elements are therefore highly electropositive and, as previously stated, form compounds that are essentially ionic in nature (Gupta and Krishnamurthy, 2004). Like most metals, the lanthanides have a gray luster or bright silvery appearance. Five of the elements (lanthanum, cerium, praseodymium, neodymium, and europium) are very reactive. When exposed to the air, they react with oxygen to form an oxide coating that tarnishes the surface almost immediately. A block of europium will be converted to an oxide in a few days or weeks. Under the same conditions, surface corrosion of a massive block of lanthanum or neodymium will occur in a few days, and a thick crust of oxide will develop in a few months.

Analytical Methods

There are a variety of methods employed to determine REE concentrations in environmental samples, such as (1) atomic absorption spectroscopy; (2) neutron activation; (3) isotope dilution thermal ionization mass spectrometry (ID-TIMS); and (4) inductively coupled plasma-mass spectrometry (ICPMS). Concentrations of REEs in unpolluted freshwater systems typically range in from parts-per-billion (ppb) to parts-per-trillion (ppt) (Lawrence et al., 2006). Therefore, a pre-concentration step such as ion exchange chromatography, Fe(OH)3 co-precipitation, or liquid-liquid extraction may be required prior to analysis. The specific method selected for analysis will provide guidance on sample preparation prior to analysis (e.g., an EPA 3000 series method).

Although each method has their advantages and disadvantages, the predominant method utilized today is ICP-MS. Listed in **Table A-1** are three established ICP-MS methods that can be utilized for the analysis of REEs. It is important to note that the EPA methods do not list REE as being successfully demonstrated by these methods. However, if REEs are to be measured they need to meet the provisions outlined in the method. Chapter K of the USGS document presented in Table A-1 was written specifically for the analysis of REEs and addresses the common matrix interference issues associated with this group of metals. Although not specifically mentioned in the EPA methods, REEs can be measured with these methods as long as the elements of interest are validated by the procedures outlined in the perspective method.

Table A-1. Analytical Methods and Sample Preservation and Holding Times for the Analysis of Rare Earth Elements

Reference Method	Method Description	Holding Time	Container	Preservation and Storage	Demonstrated Acceptable Elements
EPA 6020A	Metals in environmental samples by ICP-MS	6 months	▪ Solid - (1) 4 oz. glass jar ▪ Liquid - (1) 500 mL plastic bottle	▪ Solid – Refrigerate at 4EC ▪ Liquid – Refrigerate at 4EC; HNO_3 to pH <2	Al, Sb, As, Ba, Be, Cd, Ca, Cr, Co, Cu, Fe, Pb, Mg, Mn, Hg, Ni, K, Se, Ag, Na, Tl, V, Zn
EPA 200.8	Metals in environmental samples by ICP-MS	6 months	▪ Solid - (1) 4 oz. glass jar ▪ Liquid - (1) 500 mL plastic bottle	▪ Solid – Refrigerate at 4EC ▪ Liquid – Refrigerate at 4EC; HNO_3 to pH <2	Al, Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Hg, Mo, Ni, Se, Ag, Tl, Th, U, V, Zn
USGS Open File Report 02-223-K	REEs in geologic samples by ICP-MS	6 months	▪ (1) 4 oz. glass jar	▪ Refrigerate at 4EC	La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb
USGS Open File Report 02-223-H	Metals in aqueous samples by ICP-MS	6 months	▪ (1) 500 mL plastic bottle	▪ Refrigerate at 4EC; HNO_3 to pH <2	Ag, Al, As, Ba, Be, Ca, Cd, Co, Cr, Cs, Cu, Fe, Ga, k, Li, Mg, Mn, Na, Ni, Pb, Rb, Se, Sr, Tl, U, V, Zn, Ge, Mo, Nb, P, S, Si, Ta, Ti, W, Zr, Ce, La, Nd, Sc, Y, Fe, Al, Si

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Appendix B

Locations of REE-Producing Mines and REE-Containing Mineral Deposits in the U.S.

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Alaska	Alkalic Igneous	226	Mount Prindle (Roy Creek)	Occurrence	—	Selected material contained ama 25% REE and 15% Th. LREE more abundant in the quartz-bearing syenites.	Y	—	—	—
		160	Bokan Mountain (Ross-Adams)	Potential resource REE, Past Prod. U	—	REE-bearing pegmatites, dikes, and shear zones/fractures in central part of the complex and in veins in the outer parts & nearby country rocks. Produced 98,000 mt of approx. 1% U3O8. Because dikes generally < 1 m thick and mineralogically complex, econo	Y	Y	—	Y
		175	Dora Bay	Prospect	—	—	Y	—	—	—
	Carbonatite	77	Salmon Bay	Occurrence	—	Veins.	Y	Y	—	—
	Other Igneous-Affiliated (including Pegmatites and Veins)	312	Wolf Mountain	Occurrence	—	—	Y	—	—	—
	Other—Uncertain	753	Eagle Creek	Occurrence	—	U, Th, and REE minerals along margins of alkaline dikes.	Y	—	—	—
	Placer, Alluvial	627	Circle	Occurrence	—	—	Y	—	—	—
		629	El Dorado Creek area	Occurrence	—	Panned concentrate contained 0.029% Eu and 0.02% U.	Y	—	—	—
		630	Fortymile	Occurrence	—		Y	—	—	—
		635	Hot Springs	Occurrence	—	Buried bench gravels.	Y	—	—	—
		636	Iditarod	Occurrence	—	—	Y	—	—	—
		655	McGrath	Occurrence	—	—	Y	—	—	—
		665	Port Clarence	Occurrence	—	—	Y	—	—	—
		670	Ruby Meadows	Occurrence	—	Buried placer deposit.	Y	—	—	—
		680	Tolovana	Occurrence	—	—	Y	—	—	—

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Arizona	Other Igneous-Affiliated (including Pegmatites and Veins)	297	Mineral X	Occurrence	—	—	Y	—	—	—
		306	Signal district	Occurrence	—	—	Y	—	—	—
Arkansas	Carbonatite With Residual Enrichment	128	Magnet Cove	Past small producer rut, mag	—	—	Y	—	—	—
California	Carbonatite	59	Mountain Pass	Current producer	Molycorp (2000)	—	Y	Y	Y	Y
	Metamorphic	342	Music Valley	Occurrence	—	REE, Nb, and Th occur in veins and carbonatite dikes. Province includes Gem Park, McClure Mtn-Iron Mtn, Democrat Creek, and other occurrences.	Y	Y	Y	
	Other Igneous-Affiliated (including Pegmatites and Veins)	305	Pomona Tile Company	Occurrence	—	—	Y	—	—	—
	Placer, Shoreline	563	Soledad	Occurrence	—	In Los Angeles County.	Y	—	—	—
Colorado	Carbonatite	104	Wet Mountains	Occurrence	—	REE, Nb, and Th occur in veins and carbonatite dikes. Province includes Gem Park, McClure Mtn-Iron Mtn, Democrat Creek, and other occurrences.	Y	Y	Y	
		31	Gem Park	Past prod of vrm, Ni, Ag	—	Carbonatitic dikes. Concentrations of Th, REE, Cu, P, and vermiculite have not been fully appraised.	Y	—	—	—
		36	Iron Hill (Powderhorn, Cebolla Creek)	Ti resource/ prospect	Teck Resources Corp.	—	Y	Y	Y	
	Other Igneous-Affiliated (including Pegmatites and Veins)	307	South Platte District	Occurrence	—	—	Y	—	—	—

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Florida	Placer, Shoreline	439	Green Cove Springs	Active mine (1999); Past byproduct monazite producer	Westralian Sands (1999)	Stopped producing mon in 1994.	Y	Y	Y	—
		495	Maxville	Occurrence	—	Extension of Green Cove Springs deposit.	Y	Y	Y	—
		575	Trail Ridge (Highland Trail Ridge, Starke Trail Ridge)	Occurrence	DuPont	Marine placer.	Y	Y	—	—
		377	Boulougne	Past producer	Humphrey's Mining Co. (1979)	Deposit is exhausted.	Y	Y		
		580	Vero Beach	Past small producer byproduct mon	Riz Mineral Co. (1945)	—	Y	Y	—	—
Georgia	Placer, Shoreline	382	Brunswick-Altamaha	Occurrence	—	Marine placer.	Y	Y	Y	—
		411	Cumberland Island	Occurrence	—	Barrier island. In National Park so development unlikely.	Y	Y	Y	—
		428	Folkston	Past producer	Humphrey's Mining Co. (1979)	Deposit exhausted.	Y	Y		—
Georgia Florida	Placer, Shoreline	611	Yulee	—	—	—	Y	Y		—
		388	Cabin Bluff	Occurrence	—	—	Y	Y	—	—
Idaho	Carbonatite	68	North Fork area		—	—	Y	Y	—	—
	Metamorphic	337	Indian Creek District	Occurrence	—	Includes Wilkey Evans and Reese Esker claims, Radiant group.	Y	Y	—	—
		339	Lemhi Pass	Occurrence	—	Veins. Thorium is dominant mineralization.	Y	Y	Y	—
		340	Mineral Hill District	Occurrence	—	—	Y	Y	—	—
		341	Monumental Summit	Occurrence	—	—	Y	Y	—	—

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Idaho (cont.)	Other Igneous-Affiliated (including Pegmatites and Veins)	286	Hall Mountain Group	Occurrence	—	Mining ceased in the 1940's.	Y	Y	Y	—
	Phosphorite	733	Smoky Canyon	Byproduct producer?	—	P mine.	Y	Y	Y	—
		719	Blackfoot Bridge	Occurrence	—	? 0.1% REE in P ore.	Y	Y	Y	—
		721	Caldwell Canyon	Occurrence	—	? 0.1% REE in P ore.	Y	Y	Y	—
		722	Champ	Occurrence	—	? 0.1% REE in P ore. Phosphate mining ceased in 1986.	Y	Y	Y	—
		725	Gay and South Forty	Occurrence	—	? 0.1% REE in P ore.	Y	Y	Y	—
		727	Husky	Occurrence	—	? 0.1% REE in P ore.	Y	Y	Y	—
		730	Mountain Fuel	Occurrence	—	? 0.1% REE in P ore.	Y	Y	Y	—
		731	North Henry	Occurrence	—	? 0.1% REE in P ore.	Y	Y	Y	—
		735	Trail Creek	Occurrence	—	? 0.1% REE in P ore.	Y	Y	Y	—
		726	Henry	Past byproduct producer?	—	? 0.12% REE in P ore.	Y	Y	Y	—
		729	Maybe Canyon (Maybie)	Past byproduct producer?	—	? 0.1% REE in P ore.	Y	Y	Y	—
		736	Wooley Valley	Past byproduct producer?	—	? 0.11% REE in P ore.	Y	Y	Y	—
		734	Swan Lake Gulch	Potential producer	—	Production planned for 2004.	Y	Y	—	—
		723	Conda		—	? 0.1% REE in P ore. Phosphate mining ceased in 1984.	Y	Y	Y	—

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Idaho (cont.)	Placer, Alluvial	624	Chamberlin District	Occurrence	—	—	Y	Y		—
		667	Ramey Meadows	Occurrence	—	—	Y	Y	—	—
		650	Long Valley	Past producer	—	—	—	Y	—	—
		663	Pearsol Creek		—	—	Y	Y	Y	—
Idaho/ Caribou	Other Igneous-Affiliated (including Pegmatites and Veins)	283	Diamond Creek	Prospect	—	—	Y	Y	Y	—
Idaho/ Valley County	Placer, Alluvial	670	Ruby Meadows	—	Merlin Mining NL (1987)	7 claims near Burgdorf. Preliminary estimates indicate about 100 Mm3 with ama 0.16% Y and 0.85 g/t Ta.	Y	Y	—	—
		632	Gold Fork-Little Valley	Occurrence	—	Past gold placer producer.	Y	Y	Y	—
		279	Big Creek	Past producer	—	—	Y	Y	Y	—
		619	Bear Valley	Small past producer	—	Includes Porter placer.	Y	Y	Y	—
Illinois	Carbonatite	35	Hicks Dome	Potential resource	—	Ore contains 0.42% REO and 0.15% ThO2.	Y	Y	Y	—
Missouri	Hydrothermal Fe-Oxide	274	Pea Ridge	Potential resource	—	95 km SW of St. Louis.	Y	Y	—	Y
Montana	Carbonatite	11	Bearpaw Mountains (Rocky Boy)	Occurrence	—	Lat-long is for the Rocky Boy stock.	Y	—	—	—
		74	Ravalli County	Occurrence	—	REE in carbonate veins and dikes in metamorphic rocks.	Y	—	—	—
	Metamorphic	345	Sheep Creek	Past small producer	—	—	Y	—	—	—
	Other- F Deposits	747	Snowbird	Occurrence	—	Hydrothermal fluorite and quartz-bearing carbonate veins.	Y	—	—	—
Nebraska	Carbonatite	26	Elk Creek		—	Near Usakos. REE 0.35-1.86% in carbonatite 200 m below Quaternary and Pennsylvanian sediments.	Y	Y	—	Y

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Nevada	Other Igneous-Affiliated (including Pegmatites and Veins)	281	Crescent Peak	Occurrence	—		Y	—	—	—
New Jersey	Hydrothermal Fe-Oxide	275	Scrub Oaks	Byproduct	—	Magnetite-hematite orebody in metamorphic rocks.	Y	—	—	—
New Mexico	Alkalic Igneous	166	Caballo Mountains	Occurrence	—	Potassic dikes with postulated alkaline body at depth.	Y	—	—	—
	Alkalic Igneous	269	Wind Mountain (see Cornudas Mtns)	Occurrence	—	Eudialyte in dikes, sills, and laccoliths.	Y	Y	—	—
	Alkalic Igneous	233	Pajarito Mountain	Potential resource	—	Quartz-bearing syenite contains ama 20% eud and 5% flu. Apatite containing ama 19.2% REO has been found in the peralkaline granites. Check Mining Engineering, 1989, July, p. 515 for tonnage.	Y	—	Y	—
	Alkalic Igneous	Location N/A	Red Hills District	Prospect	—	—	Y	Y	—	—
	Carbonatite	Location N/A	Lemitar and Chupadera Mountains	Prospect	—	—	Y	Y	—	—
	Other- F Deposits	745	Gallinas Mountains	Very small past producer	—	About 65 t of bas concentrate produced in the 1950's from Cu-F veins and breccia fillings probably associated with alkalic trachyte.	Y	Y	Y	—
	Other Igneous-Affiliated (including Pegmatites and Veins)	302	Petaca District	Occurrence	—		Y	Y	—	—
		Location n/a	Captain Mountains	Potential Resource	—	Lincoln county; Est Resources: Thorium content measured from 0.01 to 1.12 percent	Y	Y	—	—
		Location n/a	El Porvenir District/ Hermit Mountain	Potential Resource	—	McLemore and others (1988) report that samples of quartzite contain traces of Th, La, and Y.	Y	Y	—	—
		Location n/a	Gold Hill Area and White Signal District	Potential Resource	—	Thorium-bearing minerals form pods and lenses within pegmatites of granite, Burro Mountains .	Y	Y	—	—
		Location n/a	Laughlin Peak Area	Prospect	—	—	Y	Y	—	—
New Mexico, Texas	Alkalic Igneous	172	Cornudas Mtns - Diablo Plateau (Wind Mtn.)	Occurrence	—	—	Y	—	—	—

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
New York	Hydrothermal Fe-Oxide	272	Mineville dumps	Past Fe producer; REE resource	Rhône-Poulenc	Apatite in mill tailings averages from 4 to more than 11% REO. Magnetite-hematite orebody in metamorphic rocks.	Y	Y	—	—
North Carolina	Placer, Alluvial	654	Marion	Past byproduct producer	Imperial Mining Co. (1990)	—	Y	—	—	—
North Carolina South Carolina Georgia	Placer, Alluvial	Location n/a	Carolina monazite belt	—	—	—	Y	—	—	—
Oregon	Carbonatite	23	Deep Creek	Occurrence	—	SE of Crane Mountain.	Y	—	—	—
South Carolina	Placer	Location n/a	Aiken County	Occurrence	National Kaolin Co.	Closed in 1958.	—	—	Y	—
	Placer, Alluvial	634	Horse Creek (Aiken County)	Past producer of monazite	—	Flood plain. Reconcentration of heavy minerals from Tuscaloosa Fmt. Includes Hollow (Holley) Creek and other drainages.	Y	—	—	—
	Placer, Shoreline	451	Hilton Head Island	Potential resource	—	Mining unlikely, resort area.	Y	—	Y	—
Tennessee	Placer, Alluvial	662	Oak Grove	Occurrence	—	Alluvial terrace.	Y	—	Y	—
		675	Silica Mine	Producer, but does not recover REO	—	HM stockpiled from past production of silica sand.	Y	—	Y	—
	Placer, Paleoplacer	662	Oak Grove	Occurrence	Ethyl Corp. (1989)	—	Y	—	Y	—
	Placer, Shoreline	511	Natchez Trace deposit	Occurrence	—	Marine placer.	Y	—	—	—
		518	North Camden (Kerr-McGee deposit)	Occurrence	Kerr-McGee (1971)	—	Y	—	—	—
		473	Kerr-McGee deposit	Occurrence	—	Marine placer.	—	—	—	—
Texas	Other Igneous-Affiliated (including Pegmatites and Veins)	291	Llano County (Williams Mine, others)	Small Past Producer	—	Several tons of pegmatite were mined prior to 1909.	Y	—	—	—

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Utah	Placer, Shoreline	Location n/a	Deep Sands	Prospect	Great Western Minerals Group	Exploratory drilling in 2008; preliminary feasibility study occurring.	—	—	—	Y
Virginia	Other Igneous-Affiliated (Including Pegmatites And Veins)	290	Little Friar Mountain (Massie)	Small Past Producer	—	Pegmatite dike in hypersthene granodiorite.	Y	—	—	—
	Other—Uncertain	775	Little Friar Mountain	Occurrence	—	—	Y	—	—	—
	Placer, Shoreline	525	Old Hickory (Stony Creek)	Active Mine (1999), no REE prod	Westralian Sands (1999)	Mine had startup problems with mining and in the separation plant.	Y	—	—	—
Wyoming	Carbonatite	10	Bear Lodge Mountains (southern)	Large, low-grade resource of REE-Th	—	Veins and disseminated deposits. Samples ranged from 112 to 30000 ppm with REE more abundant than Th. Area incompletely explored.	Y	Y	Y	Y
Wyoming/ Albany County	Alkalic Igneous	215	Laramie Anorthosite Complex	Occurrence	—	T20-22N R70-71W	Y	—	—	—
	Other Igneous-Affiliated (Including Pegmatites And Veins)	310	Tie Siding	Occurrence	—	—	Y	—	—	—
	Placer, Paleoplacer	707	Bald Mountain	Potential resource	—	Fossil fluvial placer. Little Big Horn River area. Two sites contain at least 1.0 kg mon/t of rock. Resource is poorly defined.	Y	—	Y	—
Wyoming/ Carbon County	Other Igneous-Affiliated (Including Pegmatites And Veins)	279	Big Creek	Occurrence	—	T30N, R80-81W	Y	—	Y	—
	Placer, Alluvial	618	Bates Hole area	Occurrence	—	High radioactivity.	Y	—	—	—
	Placer, Paleoplacer	714	Onemile Creek area	Occurrence	—	T18N R78W sec 6 and N/2 sec 7.	Y	—	—	—

State / Province	Deposit Type	Map Reference No (Figure 3-1)	Deposit Name	Status	Company	Comments	Orris, et al.[a]	Long, et al.[b]	Gupta, et al.[c]	Schüler, et al.[d]
Wyoming/ Fremont County	Placer, Alluvial	683	Warm Spring Creek placers	Occurrence	—	Fremont County, WY	Y	—	—	—
Wyoming/ Hot Springs County	Placer, Paleoplacer	711	Grass Creek area	Occurrence	—	Paleo-beach placers. North segment- T46N R98W secs. 8, 9, 16.	Y	—	—	—
Wyoming/ Sublette County	Other—Uncertain	765	Fremont Butte	Occurrence	—	Mineralization along cracks and veins; fault and shear-zone related. T32N R107W sec. 21, NW/4.	Y	—	—	—

[a] Orris, Greta J. and Richard I. Grauch, 2002. Rare Earth Element Mines, Deposits, and Occurrences; Open-File Report 02-189 Version 1.0; United State Geological Survey (USGS); Internet resource: http://pubs.usgs.gov/of/2002/of02-189/

[b] Long, Keith R. and Bradley S. Van Gosen, Nora K. Foley, and Daniel Cordier, 2010. The Principal Rare Earth Elements Deposits of the United States - A Summary of Domestic Deposits and a Global Perspective; USGS Scientific Investigation Report 2010-5220; US Geological survey, Reston, Virginia; Internet Resource: http://pubs.usgs.gov/sir/2010/5220/

[c] Gupta, C.K., Krishnamurthy, N. (2004) Extractive Metallurgy of Rare Earths. CRC Press.

[d] Schüler, D, Buchert, M, Liu, R, Dittrich, S, Merz, C. (2011). Study on rare earths and their recycling, OKO-insititut e.v., January.

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Gupta, C.K., Krishnamurthy, N. (2004) Extractive Metallurgy of Rare Earths. CRC Press.

Long, Keith R. and Bradley S. Van Gosen, Nora K. Foley, and Daniel Cordier, 2010. The Principal Rare Earth Elements Deposits of the United States – A Summary of Domestic Deposits and a Global Perspective; USGS Scientific Investigation Report 2010-5220;

Orris, Greta J. and Richard I. Grauch, 2002. Rare Earth Element Mines, Deposits, and Occurrences; Open-File Report 02-189 Version 1.0;

Schüler, D, Buchert, M, Liu, R, Dittrich, S, Merz, C. (2011). Study on rare earths and their recycling, OKO-insititut e.v., January.

U.S. Geological Survey (USGS); Internet resource: http://pubs.usgs.gov/of/2002/of02-189/

U.S. Geological Survey (USGS), Reston, Virginia; Internet Resource: http://pubs.usgs.gov/sir/2010/5220/

Appendix C

Process Flow Diagrams for Extraction and Processing Operations

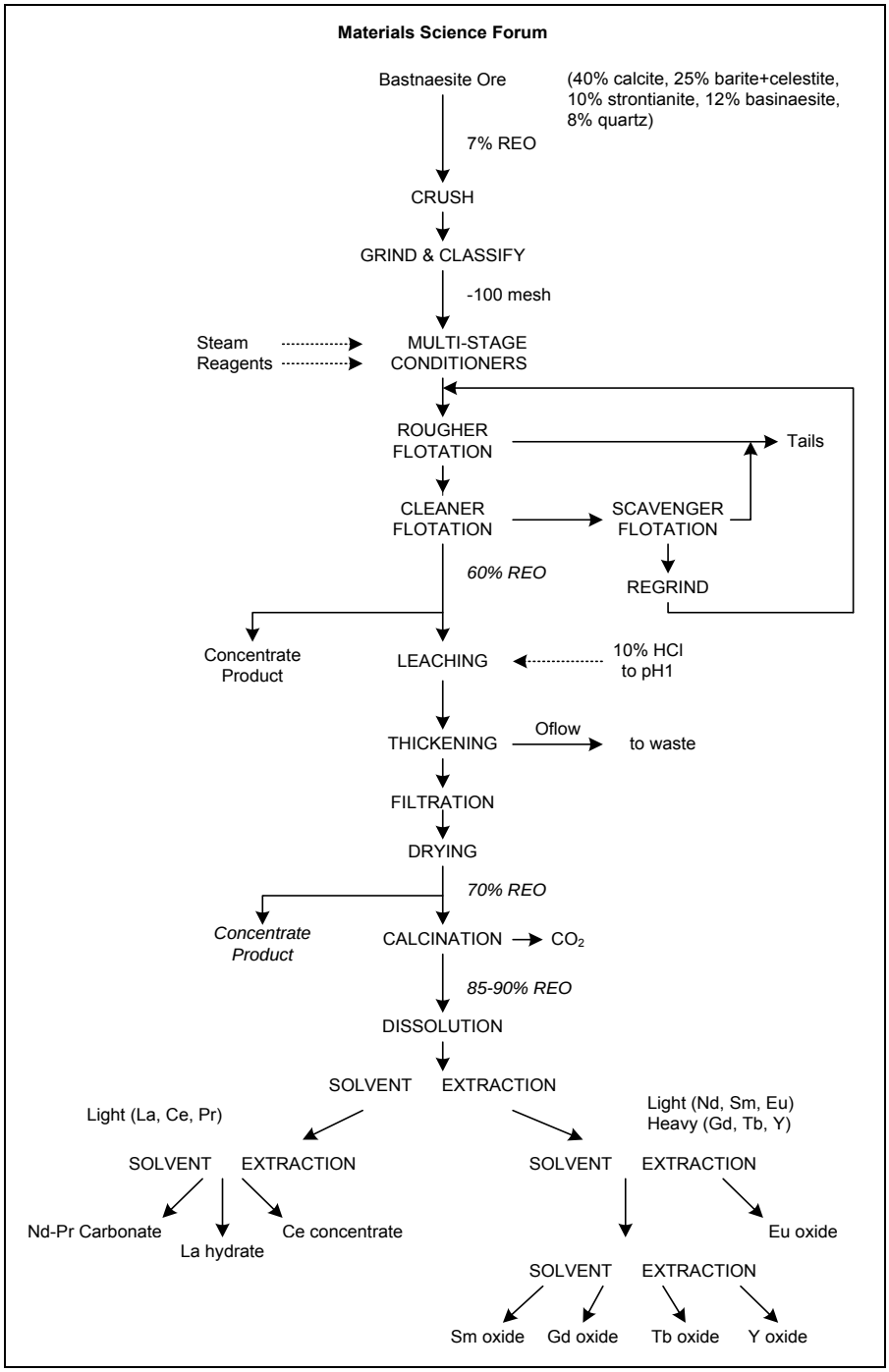

Figure C-1. Simplified flow sheet used by Molycorp at Unocal Plant, Mountain Pass, California, for recovering bastnasite (Aplan, 1988).

Figure C-1. (continued)

It is recognized that the reference date for the figure above is 1988. Given the opportunity to comment on this diagram, Molycorp's Scott Honan provided the following clarifications (personal communications, 2011):

"– after the dissolution step, the insoluble fraction was a cerium product that contained about 60% REO by weight. The other product from dissolution was the liquor that fed solvent extraction.

– the light RE elements are La, Ce, Nd, Pr. The first SX step separated these from everything else (Sm and the other heavies). Molycorp did run solvent extraction and other unit operations to further separate the heavies, and produced Eu products, Y-Eu co-precipitates, Sm, Gd and Tb products. As far as I know, Y was never produced at Mountain Pass, but it was purchased to combine with the Eu to make co-precipitates.

– the chemical form of the Nd, Nd-Pr, Ce and La products varied. I would simply call these "products" instead of specifying a chemical form."

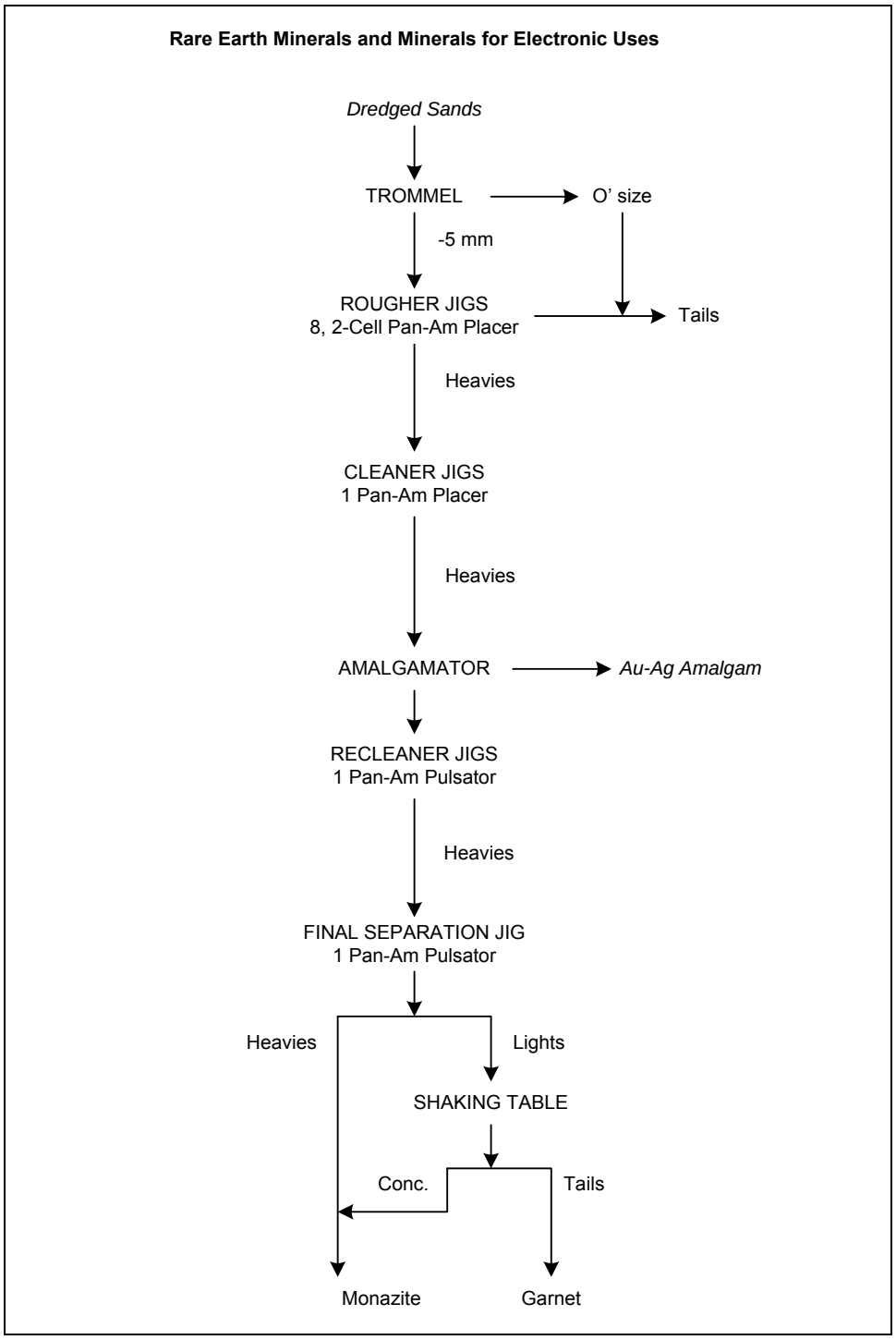

Figure C-2. Treatment of a placer monazite concentrate by dredging (Aplan, 1988).

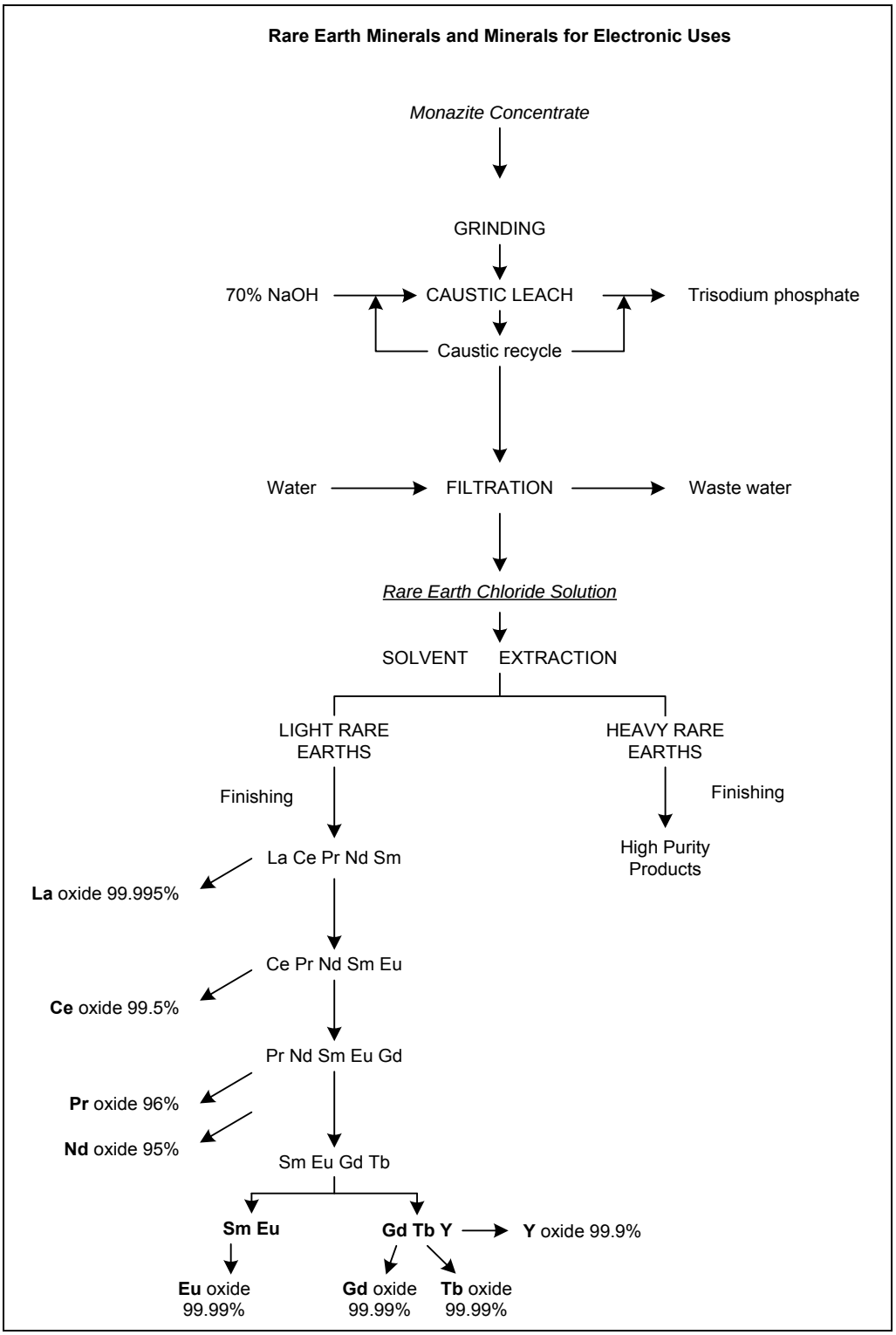

Figure C-3. Treatment of monazite concentrate for the processing of rare earths (Hart and Levins).

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