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

Office of Research and Development
National Risk Management Research Laboratory, Engineering Technical Support Center

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Engineering Technical Support Center
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Office of Research and Development
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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, but it also results in a large quantity (greater than 90 percent) of excess and unused 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. 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.

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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.

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.

Acknowledgements

David J. Reisman (retired), Director of the Office of Research and Development (ORD), Engineering Technical Support Center (ETSC) and Robert J. Weber of the EPA ORD, Office of Science Policy (OSP) served as co-principal investigators on this project. They would like to acknowledge the exemplary contribution from the RTI International team led by Coleen Northeim and consisting of Scott Guthrie, James Cunningham, and Susan Wolf. Without their assistance this document probably would not have been developed. The draft and final versions of this document were prepared under the ORD STREAMS contract (EP-C-05-060), Task 35.

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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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.

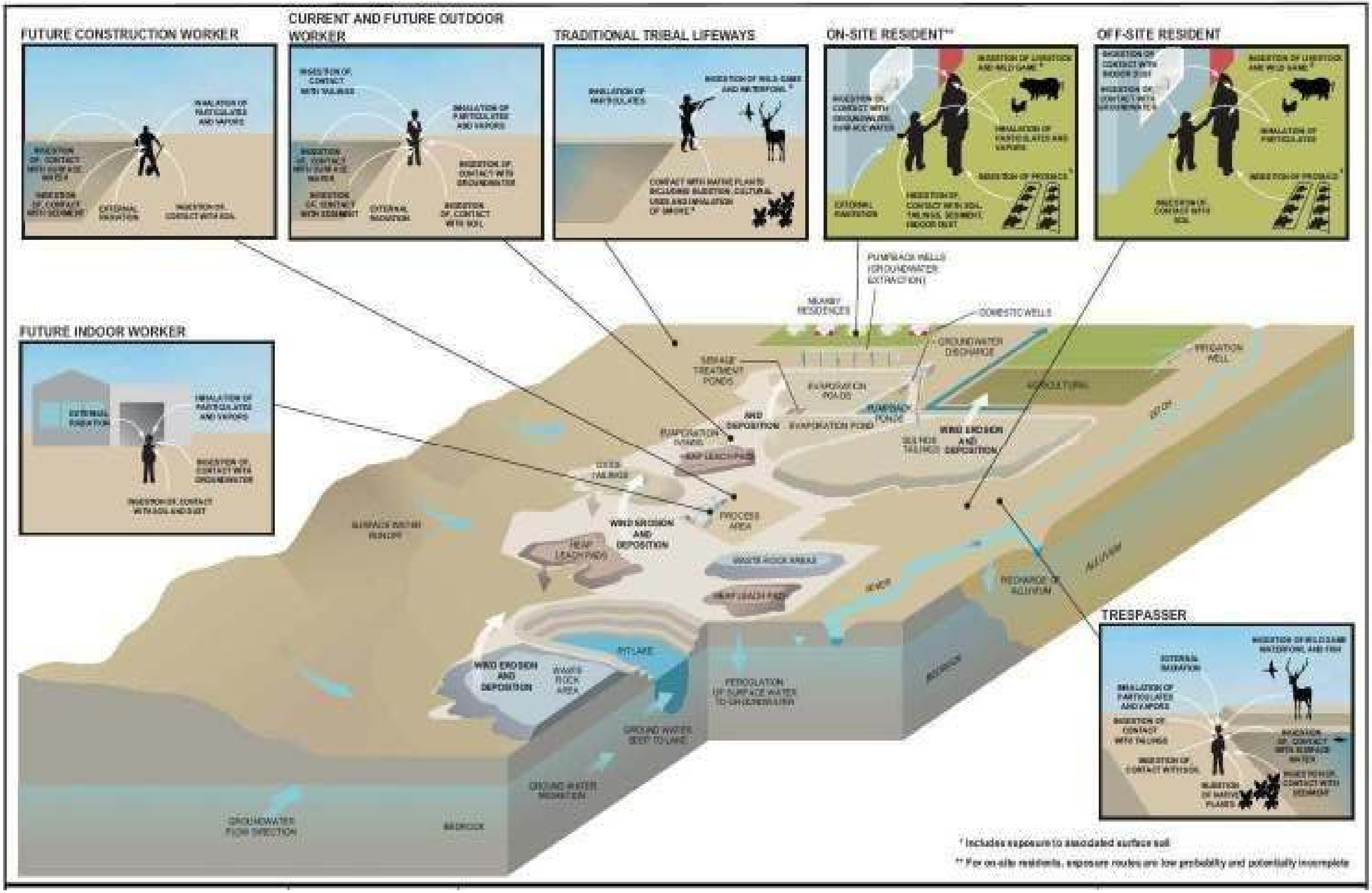

Figure 6-1. Generic above-ground hardrock mine conceptual site model and exposure pathways (U.S. EPA, 2009a).

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, cyanide 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,