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# Radiological Impacts and Regulation of Rare Earth Elements in Non-Nuclear Energy Production

**Timothy Ault *, Steven Krahn and Allen Croff**

Department of Civil and Environmental Engineering, Vanderbilt University School of Engineering, 2301 Vanderbilt Place PMB 351831, Nashville, TN 37235-1826, USA

* Author to whom correspondence should be addressed; E-Mail: timothy.m.ault@vanderbilt.edu; Tel.: +1-615-322-2697; Fax: +1-615-322-3365.

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**Abstract:** Energy industries account for a significant portion of total rare earth usage, both in the US and worldwide. Rare earth minerals are frequently collocated with naturally occurring radioactive material, imparting an occupational radiological dose during recovery. This paper explores the extent to which rare earths are used by various non-nuclear energy industries and estimates the radiological dose which can be attributed to these industries on absolute and normalized scales. It was determined that typical rare earth mining results in an occupational collective dose of approximately 0.0061 person-mSv/t rare earth elements, amounting to a total of 330 person-mSv/year across all non-nuclear energy industries (about 60% of the annual collective dose from one pressurized water reactor operated in the US, although for rare earth mining the impact is spread out over many more workers). About half of the collective dose from non-nuclear energy production results from use of fuel cracking catalysts for oil refining, although given the extent of the oil industry, it is a small dose when normalized to the energy equivalent of the oil that is used annually. Another factor in energy industries' reliance on rare earths is the complicated state of the regulation of naturally occurring radiological materials; correspondingly, this paper also explores regulatory and management implications.

**Keywords:** radiological impacts; rare earth elements; technologically-enhanced naturally occurring radioactive material (TENORM)

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## 1. Introduction

Over the last 40 years, rare earth elements (REEs) have gone from being a minor commodity, with niche uses, to constituting a major market. REE production has increased from about 20,000 t/year in the 1970s [1] to a recent demand of 130,000 t/year [2] and a projection of 200,000 t/year in 2015 [2]. The applications of REEs, which are shown in Table 1 for the US and the world, are diverse.

**Table 1.** Rare earth demand by application for the US and world in 2010 [2].

| Application | % of total REE use (US) | % of total REE use (World) |
|---|---|---|
| Catalysts | 60 | 20 |
| Ceramics | 10 | 5 |
| Metal Alloys | 7 | 18 |
| Polishing | 7 | 15 |
| Glass | 7 | 9 |
| Magnets | 3.3 | 21 |
| Phosphors | 3.3 | 7 |
| Other | 3.3 | 5 |

A significant portion of REEs is used to produce primary forms of energy (electricity, petroleum products) or to utilize energy acceptably or more efficiently (catalytic converters, batteries, light bulbs). The radiological impacts of energy-related industries are frequently attributed only to nuclear power, but REE ores are typically found in conjunction with naturally radioactive material. Thus, non-nuclear energy industries which utilize REEs will have a radiological impact, as well.

Naturally occurring radioactive material (NORM) is material containing radioactive elements such as uranium, thorium, and their decay products. Virtually all geologic material occurring in nature is radioactive to some degree, and could potentially be categorized as NORM. However, NORM is so ubiquitous that it cannot be practically managed as a radioactive waste; usually, it does not require such management because it is sufficiently dilute or is isolated beneath the surface of the earth. However, in some instances (e.g., particularly high local concentrations of thorium or radium), actions may need to be taken to protect public health.

For the purposes of this paper, a more important category of material is technologically-enhanced NORM (TENORM). TENORM is NORM in which the concentration or availability of radionuclides has been enhanced by anthropogenic activities such as mining or utilization. Examples include the scale buildup in piping used in oil production that contains elevated concentrations of radium and its decay products, or fly ash from burning coal. Many types of TENORM are not presently managed with regard to their radioactive content. However, depending on the nature of the TENORM and the applicable laws and regulations, TENORM may be categorized as a type of radioactive waste and must be managed as such (a point of confusion is that many forms of TENORM are frequently described as "NORM waste" or similar even though the materials have clearly been technologically enhanced, *i.e.*, are not in their natural state; this is particularly common outside the US). Laws and regulations concerning what constitutes TENORM and how it must be managed vary by country (and by state, within the US).

Of direct relevance to this paper is the mining and production of REEs found in conjunction with thorium, and to a lesser extent uranium, along with their respective decay products. There are different types of rare-earth-bearing minerals, with varying radiological content, that are subjected to a range of processing techniques which lead to the production of TENORM having a variable composition (radioactively and otherwise). Thus, assessing the radiological impact of REE mining can be difficult, but there is enough information available to at least put the issue in perspective. An overview of how REEs are used in energy applications will be presented to frame the discussion of radiological impacts of non-nuclear energy sources in the context of REEs. This paper will then discuss the occurrence, fate, impacts, and regulation of TENORM from REE production.

## 2. Results and Discussion

This section summarizes some of the major applications of REEs related to the non-nuclear production and utilization of energy. Furthermore, it should be noted that some of the most extensive REE uses are for applications other than energy production. These will also be discussed as they may be relevant to potential future inter-energy analyses. Table 2 summarizes the estimates for the energy-related uses that consume the most REEs (fluid cracking catalysts, wind magnets, and transportation). These estimates are approximate, but they indicate the order of magnitude of REE consumption by non-nuclear energy industries.

**Table 2.** Global REE consumption by energy application.

| Application | REE usage (t/year) |
|---|---|
| Fluid Cracking Catalysts | 35,000 |
| Wind Turbine Magnets | 2000 |
| Transportation: Diesel Additives | 200 |
| Transportation: Hybrid Vehicles | 9300 |
| Transportation: Catalytic Converters | 5100 |
| **TOTAL** | **51,500** |

The remainder of the approximate 130,000 t/year of REEs is consumed by non-energy applications of REEs including (non-turbine) magnets (17,600 t/year), metal alloys (excluding those used in hybrid vehicles, 9900 t/year), polishing agents (12,800 t/year), glass (10,700 t/year), phosphors (7700 t/year), and an assortment of other minor uses (6800 t/year) [1].

### *2.1. Fluid Cracking Catalysts (Oil)*

Fluid catalytic cracking (FCC) is an oil refining process which breaks down long-chain hydrocarbon molecules into shorter, more valuable molecules. Originally accomplished through thermal treatment, FCC has been observed to produce higher quality products and has displaced thermal treatment almost entirely [1]. This is becoming an increasingly important application for REEs. One study suggests catalysts represent 22% of REE consumption by volume, with FCC representing 64% of such catalytic use [1]. Another study asserts that catalysts occupy an even greater share of the REE market, at 62% by mass [3]. Using the average of these estimates (42%) and using Long's FCC percentage of this share (along with global REE production estimates for 2012 [2]), FCC catalysts consume approximately 35,000 t/year. The REEs used in FCC are primarily lanthanum (90%) and cerium (10%) [1].

Spent catalysts are considered hazardous due to presence of arsenic and benzene and are not typically recycled [4,5], so they are managed as chemically hazardous waste.

*2.2. Rare Earth Magnets (Wind)*

Several rare earth elements are capable of producing strong magnetic fields with only small masses (*i.e.*, they have a high magnetic density). Though catalytic applications consume the most REEs by mass, magnetic applications yield the most total revenue [1]. Many applications are unrelated to electricity production, such as electronic devices and electric vehicle motors (which are addressed separately in Section 2.3). However, the electric generators associated with wind turbines require large magnets which often contain REEs, especially neodymium. Neodymium-iron-boron magnets, among the most highly dense magnets, consume 22,500 t of REEs annually; however, only a share of this total is used in wind turbine generators [4]. Commercial wind power production comes primarily from two turbine generator designs: doubly-fed induction generators (DFIGs) and "direct-drive" systems. Only direct-drive designs, which account for 28% of new wind installations [6], use significant REE content. Direct-drive designs are further sub-divided into those that use permanent magnets with rare earths and electrically-excited synchronous generators which generally rely on copper. While electrically-excited designs have been more prevalent in the past, permanent magnet designs have rapidly become dominant [6], and we assume here that 80% of direct-drive installations will incorporate REE-based permanent magnet designs. The permanent-magnet direct-drive designs require about 200 kg REE/MW [7]. Knowing that total global wind generation capacity is expected to increase by about 44 GW/year [8], and assuming that 28.3% remains the direct-drive share of wind power in future years, this application is estimated to require about 2000 t REEs/year.

*2.3. Transportation Demands*

REEs are frequently a component of diesel fuel additives. Providing catalytic properties at small concentrations, lanthanum is the most widely used, though other elements may also be used in smaller amounts [9]. Concentrations of lanthanum are not standardized and may range from 0.001% to 0.05% [10]. It is difficult to pinpoint the relative REE content of various distillate fuels; the total annual world consumption of all distillate fuels in 2011 was about 87,000,000 barrels, or about 8,600,000 t (assuming a density of 0.832 kg/L) [11]. Higher REE-content diesels are not representative of typical bulk applications, so a value near the low end of the concentration range from [10] is assumed, 0.002%. This gives an annual demand of about 200 t REE/year.

If vehicles incorporating hydrogen fuel cells are adopted, they may eventually impact world REE consumption. REEs play a major role in several hydrogen storage designs [12,13]. However, as no clearly favored design for hydrogen storage has yet emerged, it cannot be known with certainty how this field will impact REE demand. Thus, hydrogen fuel cells are not considered in the quantitative portion of this analysis.

A major application for REEs is for various components in hybrid and electric vehicles. Multiple components may contain REE content, but their most important application is in the engine battery. For instance, the battery pack of the most popular hybrid vehicle contains 10–15 kg of lanthanum [1]. In 2010, roughly 740,000 new hybrid vehicles were registered worldwide [14]. Assuming 12.5 kg

REEs/vehicle, this equates to a demand of 9300 t REEs/year. An electrical vehicle also requires about 200 g of neodymium for permanent magnets in the motor, but this is considerably less the uncertainty of average lanthanum use in the car batteries, so it is neglected [4]. While this is currently a major consumer of REEs, two global developments could lead to a reduction in hybrid/electric REE use. The first is an expanding research effort to develop hybrid engines which require much lower or no REEs to work efficiently [15]. Furthermore, methods have been developed to recover the REE content from nickel hydride batteries; implementation is being considered by leading vehicle manufacturers [16]. However, it should be noted that end-use recycling of REEs generally requires extensive physical and chemical processing, and a number of applications have proved to be challenging. The sulfuric acid leach process which has been proposed for recycle of nickel hydride batteries has yet to be demonstrated to be economically viable [17].

REEs are not only relevant to hybrids and electric vehicles. Because of its ability to catalyze the conversion of nitrous oxides to elemental nitrogen, cerium is used in most catalytic converters (CATCONS). CATCONs are present in 85% of the cars and light trucks manufactured in the world as of 2013 [18]. Table 3 shows the amount Ce present, on average, in the CATCONS of certain types of vehicles:

**Table 3.** Cerium content in CATCONS of different vehicle types as of 2010 [18].

| Category | Number of vehicles of this type (millions) | Average total Ce in CATCON (g) | Total REE per vehicle type (t) |
|---|---|---|---|
| Cars/Light-Duty Trucks | 230.4 | 80 | 18,000 |
| Heavy-Duty Vehicles | 11.62 | 100 | 1200 |
| Motorcycles | 8.212 | 23 | 190 |
| TOTAL | - | - | 19,400 |

However, the recycling of REEs from this application lowers the effective annual demand to about 5100 t/year [1]. It should also be noted that most modern cars have significant numbers of small magnets to power light-weight motors for equipment such as power windows, sound equipment, sensors, and others. Many of these rely on rare-earth-driven permanent magnets; however, it is unclear what the total REE usage from non-drive motors in cars is. Because the size of the magnets used in the non-drive motors of cars are generally very small (even compared to the 200 g of neodymium used in hybrid vehicle motors [4]), we presently assume this usage to negligible.

### *2.4. Solar Panels*

REEs have been used in several photovoltaic cell designs. The complexes that several REEs form (especially Eu and Ce) absorb certain wavelengths particularly effectively [19,20]. However, no dominant solar cell design, or range of designs, has emerged globally. As such, the future role of solar cells in global REE consumption remains unclear. In a 2012 European Parliament report projecting the future metal demand from photovoltaic applications, Ce is briefly mentioned, but its use was not considered significant to warrant quantitative analysis [21].

### *2.5. Radioactive Tracers for Exploration (Oil, Gas)*

Though not a major consumer of REEs by mass, geochemical tracers used to identify oil and gas may use REEs. The usefulness of REEs for this application has been explored to an increasing extent since the advent of enhanced recovery techniques such as hydraulic fracturing (fracking) [22].

### *2.6. Phosphors*

REEs are valued for their luminescent properties (although this may be stretching the limits of what falls under the umbrella of energy applications). They are applied to fluorescent lamps, cathode ray rubes (CRTs), and semiconductor light-emitting diodes (LEDs) [23]. A number of REEs are useful in this application; however, yttrium is the most heavily deployed for this application. Phosphor applications currently use about 8000 t REEs/year [1]. Since most of these applications do not clearly fall under the scope of energy production, this figure is not included in the total estimated REE demand of energy industries—it is provided for information.

## 3. Radiological Material in REE Ores

In 2010, China produced 97% of the world's REEs, with India producing 2% and a handful of other countries (Malaysia, Brazil, South Africa) producing the small remainder [2]. However, the US's Mountain Pass mine has re-opened after over a decade of closure, with planned production rates that would represent a significant portion of global demand. Thus, this paper assumes 90% contribution from China and 10% from Mountain Pass, although this ratio could change if China further restricts its REE exports (see [2]). Australia's Mount Weld site may also play a significant role in near-term REE recovery, but it is not yet operational and has been omitted from present analysis.

While only about half of China's REEs come from Bayan Obo, an iron mine which recovers REE minerals as a by-product, it is assumed herein to be representative of other Chinese REE mining sites. Mountain Pass, which recovers ore solely for its REE content, is currently both the only dedicated REE mining operation and the only REE processor in the US. For near-term applications of REEs (outside of minor REE producers like India and Brazil), China and the US are likely to constitute essentially all major REE production. This section considers all REEs as a group on a mass basis. Table 4 shows the radiological material (effectively thorium) that is retrieved for a fixed amount of REE recovery. A discussion of the derivation of these values is presented in Sections 3.1 and 3.2.

**Table 4.** Summary of radiological content of REE mining.

| Impact | Value |
|---|---|
| kg of Th Extracted/t REE | 6.7 |
| Total t/year REE Used Annually by Non-Nuclear Energy Industries | 51,500 |
| Total t/year of Th Extracted Annually due to Non-Nuclear Energy Industry REE Demands | 350 |

### *3.1. Bayan Obo*

A few Chinese mines recover REEs, but the largest producer by far is Bayan Obo in Inner Mongolia. In spite of the mine's dominance of global REE production, its most important product, by both mass and revenue, is iron ore. Certain veins at Bayan Obo contain both significant iron ores and REEs. The REE content of these veins is primarily in the form of the thorium-bearing minerals monazite (25%) and bastnasite (75%) [24].

A Chinese study reports that the REE-producing portion of Bayan Obo contains 34% iron, 5% rare earth oxides (REO), and 0.032% Th oxide [25]. Renormalizing to ignore the oxygen content, this equates to about 4.3% REEs and 0.028% Th. An International Atomic Energy Agency (IAEA) report contains similar values, 5%–6% REEs and 0.04% Th oxide (or 4.7% REEs and 0.035% Th) [24]. Taking the average of these two sources, the ore is assumed to be 4.5% REEs and 0.032% Th. Thus, on average for the production of 1 t of REEs, 7.1 kg of Th are contained in the ore. A geological survey examined 14 monazite samples and three bastnasite samples from Bayan Obo [26]. The monazite samples averaged 2.00 ppm U, while the bastnasite samples averaged 0.38 ppm U. In short, the U content is small compared to the Th content.

Of Bayan Obo's thorium content, 96%–98% ends up in solid waste, 0.1%–0.5% leaves in exhaust gas, and 0.6%–2.0% goes to liquid effluents [25]. The management of the solid and liquid wastes associated with REE mining and extraction will be discussed later in the paper.

### *3.2. Mountain Pass*

Although a number of high-grade REE deposits occur in the US, the largest known deposit is Mountain Pass in California [27]. More importantly, it is the only REE mine in the US which is active. It was once the world's largest REE producer, but the increased production from Bayan Obo, environmental compliance challenges, and falling REE prices led to its closure in 2002. However, export restrictions from China and consequent REE price increases have led to Mountain Pass being re-opened, with plans to produce 20,000 t of REEs annually [28]. At projected world production levels for 2014, this would represent 10% of the global total [2] (hence the 90%–10% weighting scheme used for Bayan Obo and Mountain Pass, respectively, assumed above).

Although both bastnasite and monazite (REE-bearing minerals) occur in parts of the Mountain Pass property, the REE product is primarily extracted from bastnasite [29]. The bastnasite ore at Mountain Pass contains 0.02% thorium [30] relative to 8.9% rare earth oxide [29], or 7.6% REEs. This means that for every 1 t of REEs produced, 2.6 kg of Th is extracted as well. The U content is considerably smaller than the Th content [30]. Using the 90–10 production weighting scheme for Bayan Obo and Mountain Pass, the worldwide ratio of potential thorium production to actual REE production is 6.7 kg of Th extracted/t REE produced. Mountain Pass's radioactive waste management strategy will be discussed later in the paper.

### *3.3. Occupational and Public Radiation Dose Impacts of REE Mining*

The typical worker at Bayan Obo experiences a dose of 0.24-0.7 mSv/year [25]. The center of this range, 0.47 mSv/year, is taken as the average individual worker dose for subsequent calculations. The Bayan Obo mine employs up to 6,000 personnel [31] and produces 55,000 t of REE annually [27]. Thus, the collective occupational dose can be calculated to be 0.051 person-mSv/t REE. For comparison, the Akouta mine of Niger (annual production: 1506 t U/year) experienced an average worker dose of about 4.7 mSv/year (the utility who operates the Nigerien mines provides two different averages, one for its employees (5.33 mSv) and one for subcontractors (4.1 mSv) [32]. The breakdown of how many employees fall into each category is not provided, so the average of the two figures (4.7 mSv) is assumed) [32]. Given a workforce size of about 1200, this equates to a collective occupational dose of 3.7 person-mSv/t U. Open-pit uranium mining in the US results in about an order of magnitude lower dose than in Niger (0.369 person-mSv/t U [33]), but in either case there is apparently less exposure associated with REE mining than with U mining.

Similarly, the incremental public exposure in the surrounding city of Baotou (pop. 1.78 million) attributable to Bayan Obo operations has been estimated to be 0.043 mSv/year, on average, for those living in the "soil-contaminated area" [25]. Assuming that this corresponds to the dose rate in the mining district portion of the city, which has a population of 26,050, the collective public dose is 0.02 person-mSv/t REE. The population density around Bayan Obo is much higher than what is typically found around intensive mining areas in the US; thus, the estimated collective public dose is probably considerably higher than what would actually be observed in the US.

However, it is not appropriate to attribute the entirety of these impacts to REE production, since the primary commodity at Bayan Obo is iron ore. Though annual iron production levels at Bayan Obo can be found, they are confounded by the fact that Bayan Obo retrieves much of its iron from the West Pit, which has a much lower REE and Th content than the Main and East pits, where the REEs are recovered [25]. Assuming that the ratio of iron produced to REEs produced at the Main/East pits corresponds to their elemental abundance there (34% to 4.3% [25]), this gives REE-attributed impacts of 0.0065 person-mSv/t REE for occupational dose and 0.0025 person-mSv/t REE for collective public dose. While this division of impacts is weighted by mass, it could also be possible to assign weights by relative product value; however, this value would fluctuate based on commodity prices.

At Mountain Pass, a 1992 study found an average annual worker dose of about 0.75 mSv/year, with roughly equal contributions coming from external gamma rays and dust inhalation [24]. In its re-opening, Mountain Pass operators have laid out more thorough guidelines to minimize occupational and environmental impacts [30]. For the purposes of comparison, between the late 1980s and 2002, the average individual occupational dose for uranium recovery has decreased by a factor of about 2.6, and has generally leveled off since 2002 [34]. This reduction factor is assumed to apply to the case of Mountain Pass, resulting in an individual dose of 0.29 mSv/year. At steady-state operation, Mountain Pass intends to employ 200 personnel for a production of 20,000 t REE/year [35]. This would result in a collective occupational dose of 0.0029 person-mSv/t REE. When using the 90–10 weighting scheme, this produces an average impact from both mines of 0.0061 person-mSv/t REE. Since no public dose estimates are available for Mountain Pass, the public dose is taken entirely from Bayan Obo's figure. Table 5 summarizes the results described above.

**Table 5.** Summary of radiological impacts of REE mining.

| Impact | Value |
|---|---|
| Total Occupational Dose (person-mSv/t REE) | 0.0061 |
| Total Public Dose (person-mSv/t REE) | 0.0025 |

It should be noted that the estimated public dose is so close to the occupational dose primarily due to large population presently immediately around Bayan Obo. For the total REE required annually by non-nuclear energy industries, this is equivalent to 330 person-mSv of occupational dose.

This is about the 60% of the collective dose associated with a 1 GWe-yr pressurized water reactor (560 person-mSv) [36]. Also, the total REE dose is spread over about 10,000 workers, whereas the current average workforce at a PWR is about 550 [34].

## 4. Guidelines and Regulations for TENORM Management

While the magnitude of radiation exposure from REE mining may not seem significant, potential complications may arise from the regulatory and management requirements associated with REE recovery designed to address potential environmental impacts. There is no universally accepted approach for the management of NORM and TENORM wastes. Laws and regulations have been developed, but their substance and implementation vary. This section will begin with an overview of international guidelines and will move on to US TENORM regulations.

### *4.1. IAEA Safety Standards Series*

The IAEA has developed safety standards pertaining to the hazards associated with Th-bearing (and to a lesser extent, U-bearing) material that is removed during certain mining processes, particularly those pertaining to REEs. General recommendations are based on the language of the International Basic Safety standards. These standards prescribe that, while most material is not regulated with regards to radiation safety, public exposure from effluent discharges or the disposal of radioactive waste should most likely be considered for regulation, unless an exemption is granted [37].

A general "rule of thumb" is to only regulate streams with a total specific activity from Th or U and their decay products of 1 Bq/g or higher [38]. If this threshold is exceeded, a three-step process is recommended [24]:

- Initial Assessment: The process, materials, and associated exposures are investigated. The most likely pathways are external exposure from gamma radiation and internal exposure from radionuclide-bearing dust, although the inhalation of gaseous radon (Rn-220 from Th and Rn-222 from U) may also need to be considered.
- Regulation: There are four primary options for managing exposure from TENORM. These are listed below with increasing restrictiveness:
    - Exemption: Regulation is not necessary for the site or process.
    - Notification: The responsible party must submit notification to the relevant regulatory body about the practice they will carry out.
    - Registration: The responsible party is obligated to provide sufficient protection to exposed individuals through a minimal number of prescribed methods. Adherence to these measures may be monitored and reviewed by the regulatory body.
    - Licensure: The process requires a license and is subject to stringent controls to reduce exposure.
- Control: The extent of the measures used is commensurate with the type and concentration of material present as well as the option for the regulation that has been adopted (see above). In many sites with TENORM, the extent of exposure is sufficient low that relatively straightforward measures may be taken to reduce the risk to acceptable levels. Simply storing TENORM materials in an unoccupied area may be sufficient, with fencing and warning signs

being applied. In situations where dust is an issue, adopting Occupational Health and Safety (OHS) standards to minimize dust exposure in general can relieve much of the problem. Engineered controls, modified working procedures, and specialized respiratory equipment (in order of decreasing preferability) may be required when exposure is particularly significant. In any situation, worker awareness and training is highly recommended.

International Transport Regulations indicate specific control measures based on particular concentrations for different isotopes. These standards are not specific to TENORM and apply to the transportation of radioactive material in general. The guidance includes formulae for determining material classification [39].

Aside from the transportation recommendations, IAEA guidelines are intentionally generic, recognizing the diversity of situations involving TENORM and the difficulty of selecting a single approach which is appropriate for all situations.

### *4.2. TENORM in the US*

The US Environmental Protection Agency (EPA) is the "starting point" for determining which regulations apply to a prospective TENORM site. NORM is said to "become" TENORM when it is purposefully or inadvertently concentrated, either in waste streams or as a product [40]. The EPA only performs TENORM regulation.

The general approach to the regulation of material from mines is to break down the life cycle of the mine into four stages: exploration, mine development, ore extraction and processing, and mine closure. Radioactive content is not considered until the mine development phase, when the potential production of TENORM must be accounted for during design. Controls must be implemented to manage the tailings of REE processing. Commonly implemented controls are the precipitation of radium from liquid effluent and dust-preventive measures [40]. The radioactive mining and milling wastes of an REE mine are regulated under several national regulations, such as the Safe Drinking Water Act for liquid effluents and the Clean Air Act for gaseous emissions [40]. Furthermore, regulations of TENORM are sometimes implemented at the state level [41].

It should be noted that the US Nuclear Regulatory Commission (NRC) does not regulate REE mines, processing facilities, or TENORM, and would not unless thorium and/or uranium were being chemically processed/recovered. For comparison, the NRC does not regulate open-pit and underground uranium mines; regulation begins with uranium mills. In-situ leaching mines *are* regulated by the NRC since they perform some of the chemical treatment that a mill would [42]. If thorium were chemically treated and processed to produce nuclear fuel, such processing would be reviewed by the EPA and the NRC for regulatory purview, similar to how uranium by-product recovery has been managed at the phosphate mines of central Florida [43].

### *4.3. Case Studies of Radiological Issues with REE Mining and Production*

There are a number of cases where the radiological content of REE ores has presented a challenge from a regulatory standpoint, a health standpoint, or both. Several of the more well-documented cases are discussed below.

#### 4.3.1. Amang Processing Facility (Malaysia)

Malaysia has experienced a history of challenges with TENORM. The nation is a major producer of tin, which is generally found in the mineral cassiterite. In Malaysia, cassiterite is often found with an array of potentially valuable minerals that is locally referred to as *amang*. One significant component of amang is monazite which has the higher thorium concentration of the two primary REE minerals. Regardless of whether the monazite is recovered for REEs, any processing of amang leads to waste management challenges and radiological risks [44].

The proposed Mount Weld mine site in Australia contains a vast collection of REEs and Group V elements (vanadium/niobium/tantalum). While Mount Weld's ore is to be concentrated on site, plans called for transportation of the concentrate to Malaysia, where construction was initiated on a processing facility. Given previous Malaysian experience with TENORM from amang processing, though, public unease was vocalized both domestically and abroad [45].

In 2011, the Malaysian government requested that the IAEA carry out a formal review of the potential radiation effects of the facility while it was still under construction, as well as a review of the structure of Malaysia's Atomic Energy Licensing Board (AELB) [46]. In general, the IAEA found the operations of both the proposed facility and the AELB to adhere to international standards. However, the IAEA made recommendations, including that the AELB should:

- Request a waste management plan from Mount Weld's operating company prior to next phase of licensing, including disposal siting, decommissioning strategy, gaseous effluent management, *etc.*
- Request an exposure and environmental monitoring plan.
- Establish a means of regularly incorporating evolving international standards.
- Enable transparency and communication with the public.

The Malaysian amang processing facility is fairly ordinary by global REE processing standards and is expected to result in slightly lower doses than other facilities of its type [46]. However, the visibility of the review has led to greater visibility of the global REE licensing process. Though IAEA's recommendations have somewhat delayed startup of the Malaysian facility, the project is still being pursued. As of 2013, the facility has been granted a temporary operating license and has submitted plans for a permanent waste disposal facility [47].

#### 4.3.2. REE Processing Facilities in India

At many locations along India's southern and eastern shores, valuable heavy mineral sands can be found. The accessibility of these beach sands can make mining them profitable. The content varies by location; ilmenite (titanium ore) is generally the primary product, though cassiterite (tin ore) may also drive production [48]. Many of these sites contain significant amounts of monazite (REE-bearing mineral with high Th content), among other potential by-products. As such, plants are sometimes operated to recover the REE content as a byproduct. Occasionally, even the Th content is recovered because of India's interest in the thorium fuel cycle, which is currently unique among global REE processing facilities.

Both the working conditions in and the effluent streams from these REE processing facilities have been examined. The specific activities of the liquid effluent streams were observed to fall below IAEA's recommended thresholds for regulation in all cases, but external gamma ray exposure and internal dust inhalation were deemed to be sufficient to necessitate monitoring and protection measures for workers [49]. The liquid wastes have low radionuclide concentrations, but they are nonetheless scrubbed for removal of Ra-228 prior to release into the environment [50].

The solid wastes from these facilities can represent a radioactive waste management challenge. Depending on whether phosphates and/or thorium are recovered from monazite, there can be several solid waste types to manage (insoluble/unreacted sludge, mixed cake, and effluent treatment cake). The radioactivity of various solid wastes from REE processing ranges from 100–10,000 Bq/g [50]. Concentrated solid wastes are stored on-site in silos, which are engineered structures with shielding. Monitoring efforts to date indicate that these measures have been effective in limiting the radiological impacts beyond plant boundaries.

REE recovery has persisted long enough in India that at least one facility has gone through the process of decommissioning. Activity levels from Ra-228 were observed to be significant in some areas, particularly in vessels where REE decontamination occurred. Various waste items were managed as follows [51]:

- Sludge was removed from pipes, vessels, *etc.* and loaded into polyethylene-lined concrete casks.
- Rubber linings were scraped off tanks and placed in concrete casks.
- Wood and plaster components were chopped up and placed in high-density polyethylene (HDPE) bags.
- Electrical equipment was decontaminated and salvaged for re-use.
- The buildings were demolished, and the rubble was managed as non-radioactive waste.
- Waste-bearing concrete casks and HDPE bags were disposed of in near-surface concrete trenches.

#### 4.3.3. Mountain Pass: Before and After Closure

Mountain Pass began operating in the 1950s, but the period of peak production was between 1965 and 1995. In addition to REE price decreases primarily resulting from competition from Chinese mines like Bayan Obo, Mountain Pass encountered regulatory challenges that contributed to the mine's closure in 2002.

While a complete picture of the working environment at Mountain Pass prior to closure is difficult to piece together from available documents, the most serious issues appear to relate to the site's wastewater management strategy. This wastewater, which had a significant concentration of thorium and its decay products, was piped to evaporation ponds near the dry bed of Ivanpah Lake. Accidents occurred where wastewater that leaked from the ponds reached Ivanpah Lake [52]. These events led to Mountain Pass's ownership being sued, successfully, by San Bernardino County.

As a part of reopening this facility, modifications have been laid out for existing facilities and procedures at Mountain Pass. Among these modifications is a revision of the evaporation pond system, updated mineral recovery facilities, and prompt decommissioning of unused facilities that are still standing [30].

## 5. Conclusions

REEs are integral to a number of applications of non-nuclear energy production. Such uses account for a significant portion of total REE use. This paper has estimated a total rate of REE consumption from non-nuclear energy industries of 51,500 MT/year; however, we have noted several categories, such as hydrogen-fueled vehicles and photovoltaic cells, which could change these estimates as future technology trends emerge. As discussed in this paper, the TENORM associated with REE mining and processing can create challenges both from a health and a regulatory standpoint. The overall magnitudes of the external radiation dose due to REEs are small (0.0061 person-mSv/t REE), when compared to nuclear reactor operations; however, there may be localized instances where the impacts of REE mining would be particularly high. Further, the management of TENORM has caused issues in the past and appears to be an increasingly contentious topic. The details presented in this paper suggest that TENORM generation may be a metric of interest when considering the compositions of future energy portfolios.

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**Author Contributions**

All three authors were thoroughly involved in the development of the concepts presented in this paper. Timothy Ault conducted the numerical analyses, researched energy applications for REEs and the radiological impacts associated with REE mining, and led the writing for most sections of the paper. Steven Krahn led the research and development of regulatory sections of the paper, helped to scope the section on energy applications for REEs, and served a comprehensive internal review role for all sections of the paper. Allen Croff collaborated on framing and supporting the research, and served a comprehensive internal review role for all sections of the paper.

**Conflicts of Interest**

The authors declare no conflict of interest.

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