**Radon Risks in the Rare Earth Industry: A Critical Review of Exposure Pathways, Health Impacts, and Policy Gaps**

**Abstract**

The accelerating demand for rare earth elements (REEs) to fuel clean energy and high-tech industries has sparked a resurgence in mining and processing activities worldwide. While the strategic and economic significance of REEs is well recognized, the radiological hazards associated with their extraction—especially from thorium- and uranium-bearing ores like monazite and bastnäsite—remain critically understudied. This review highlights radon emissions as a neglected occupational and environmental health issue within the REE supply chain. It consolidates evidence on radon generation mechanisms, exposure pathways during different production stages, and the health outcomes tied to chronic radon inhalation. Epidemiological findings from regions such as Bayan Obo and Nam Xe are presented alongside an evaluation of international regulatory frameworks, which reveal striking inconsistencies and gaps in radon-specific protections. The analysis identifies systemic deficiencies including limited monitoring mandates, outdated exposure thresholds, and inadequate community engagement. We propose a five-pronged policy approach involving modernized exposure limits, continuous surveillance, classification of REE wastes as radiological hazards, long-term health and environmental tracking, and proactive stakeholder education. Bridging these regulatory and awareness gaps is essential to ensure that the critical push for REEs does not impose avoidable health burdens on workers and local populations.

Keywords: radon; rare earth elements; NORM; radiation protection; occupational health; policy gaps

1. **Introduction**

Rare earth elements (REEs), comprising 17 chemically similar metals including the lanthanides, yttrium, and scandium are critical to modern technologies such as wind turbines, electric vehicles, and defense systems (Balaram, 2019). Global production exceeded 350,000 metric tons in 2023, with China accounting for approximately 70% of the supply (U.S. Geological Survey, 2024). However, many of the minerals that host REEs particularly monazite, bastnäsite, and xenotime also contain significant concentrations of thorium and uranium, making them sources of naturally occurring radioactive materials (Kotb et al., 2023; IAEA, 2011).

The decay of these radioactive elements produces radon-222 and radon-220 (thoron), both of which are odorless, tasteless, and carcinogenic gases classified as Group 1 carcinogens by the World Health Organization (WHO, 2009). Although radon exposure is tightly regulated in uranium mining, REE operations often fall outside such frameworks due to inconsistent classification and limited regulatory oversight (IAEA, 2015).

As the world intensifies its shift toward renewable energy and digitalization, the urgency of addressing radiological risks across the REE value chain grows. This is especially true in low- and middle-income countries where environmental regulations may lag behind industrial expansion. While some nations have begun applying uranium-equivalent standards to REE operations, many others treat these facilities as conventional mines, failing to account for radon’s mobility, persistence, and potential for cumulative exposure in both occupational and community settings.

This narrative review draws on peer-reviewed publications, international agency reports, and policy documents published between 2000 and 2024. Relevant sources were identified through targeted keyword searches in databases such as Scopus, Web of Science, and Google Scholar using terms including “radon,” “rare earth mining,” “NORM,” “occupational exposure,” and “regulatory frameworks.” The review examines radon generation mechanisms, exposure pathways during REE production stages, associated health outcomes, and existing regulatory responses. The goal is to identify regulatory gaps across the REE value chain and propose opportunities for improved radiation protection.

**2. Global Landscape of Rare Earth Mining and Processing**

**Major Producing Regions**

Global REE production is highly concentrated, with China contributing approximately 70% of the global output, primarily from the Bayan Obo deposit in Inner Mongolia, the world’s largest rare earth mine (Weng et al., 2013; U.S. Geological Survey, 2024). Other major producers include the United States, with about 45,000 metric tons from Mountain Pass; Australia, with roughly 18,000 metric tons from Mount Weld; and emerging operations in Africa, particularly in Burundi and Nigeria (U.S. Geological Survey, 2024). This evolving distribution reflects geopolitical efforts to reduce reliance on Chinese supply chains by diversifying sources of REE production.

**Ore Mineralogy and Geological Context**

The two dominant REE minerals are bastnäsite (a fluorocarbonate) and monazite (a phosphate), which differ significantly in their thorium and uranium content (IAEA, 2011). Bastnäsite is abundant in carbonatite-hosted deposits such as Bayan Obo (China) and Mountain Pass (USA), whereas monazite is prevalent in heavy mineral sands in Australia and South Africa (Weng et al., 2013). Monazite ores typically contain 5–10% thorium dioxide (ThO₂) and 0.2–0.4% uranium oxide (U₃O₈), making them inherently radioactive (Kotb et al., 2023). Even bastnäsite, though lower in radionuclide content, can contribute to measurable radon release, and its classification under NORM regulations is justified (Zhang et al., 2022; IAEA, 2011).

**Processing and Separation Hubs**

REE processing often occurs in different countries from the mining site, highlighting a transnational model that complicates regulatory oversight. For example, Lynas Corporation mines REE ores in Australia but ships the concentrate to Malaysia for chemical separation and refining (Kuan et al., 2016). This model has drawn scrutiny, particularly in Malaysia where legacy issues with thorium-rich tin tailings led to public protests and IAEA evaluations of the Lynas facility (Kuan et al., 2016). By contrast, China typically integrates mining and processing domestically under environmental quota systems, although illegal mining in southern regions has historically undermined regulatory enforcement (Ault et al., 2015).

**Trends and New Projects**

A new wave of REE projects has emerged in countries such as Canada (Nechalacho), Tanzania (NdPr), and Greenland, driven by growing demand for clean energy technologies and electric vehicles (Dutta et al., 2016). Many of these deposits are monazite-rich and exhibit thorium concentrations ranging from 3–7%, similar to South Africa’s Steenkampskraal project (IAEA, 2011). These developments underscore the urgent need for harmonized standards and robust radiological risk assessment frameworks, particularly in emerging African economies where regulatory capacity remains limited.

**3. Radiological Hazards of Radon in REE Ores**

**Radon Generation Pathways**

Radon isotopes are produced through the radioactive decay of uranium and thorium within REE-bearing minerals. Specifically, uranium-238 decays to radon-222 (half-life: 3.8 days), while thorium-232 decays to radon-220 (thoron; half-life: 56 seconds) (Wang et al., 2020). Monazite and xenotime often contain several percent thorium, making them major sources of thoron, while bastnäsite, despite its lower radionuclide content, may still emit some radon when finely crushed during beneficiation (Kotb et al., 2023; IAEA, 2011). Crushing and grinding increase the surface area and pore connectivity of the material, enhancing radon emanation into the mine or processing atmosphere.

**Isotope-Specific Risks**

Radon-222, due to its longer half-life, is capable of diffusing over greater distances and accumulating in underground mines, storage buildings, and homes. Thoron (radon-220), while more short-lived, can cause acute local exposure near the source material. Both isotopes decay into solid progeny such as polonium-218, lead-214, and bismuth-214 that readily attach to airborne dust particles. When inhaled, these progeny deposit in the lungs and emit alpha particles that damage epithelial tissue, contributing to a well-documented increase in lung cancer risk (WHO, 2009).

**Occupational Exposure Hotspots**

In REE mining environments, inadequate ventilation during excavation, crushing, and milling processes can result in elevated radon and thoron accumulation. At China’s Bayan Obo mine, thoron progeny concentrations in ore crushing zones were reported to be 3.7 to 12 times higher than radon-222 progeny, due to thorium-rich dust particles (Chen and Chen, 2008). Underground mines are particularly vulnerable to radon buildup without mechanical airflow systems, while enclosed ore-processing areas also face transient spikes in radon levels during handling and storage (Barakos et al., 2016).

**Environmental Emissions and Community Exposure**

Radon also poses risks beyond the occupational setting. It can migrate from tailings impoundments and mine waste into adjacent communities (IAEA, 2011). Although outdoor conditions generally dilute radon concentrations (WHO, 2009), poor waste management practices such as uncovered dry stacks can allow radon to accumulate near residential zones, especially under stagnant weather conditions. For example, concerns over elevated radon levels near Malaysia’s Lynas facility, documented in local reports, highlight how inadequate containment and public communication can trigger both health risks and social unrest (Kuan et al., 2016; Wang et al., 2020). These cases underscore the need for integrated environmental policies that consider both occupational exposure and emissions impacting nearby populations.

**4. Epidemiological Evidence on Radon Exposure and Health Outcomes**

**Radon and Lung Cancer Risk**

There is strong and consistent epidemiological evidence linking radon exposure to lung cancer. Pooled studies involving uranium miners have shown a 16% increase in lung cancer risk for every 100 Bq/m³ of prolonged radon exposure (U.S. EPA, 2003). Residential studies confirm that the risk persists even at relatively low concentrations, reinforcing radon’s classification as a leading environmental carcinogen. Globally, radon is estimated to contribute to 3–14% of all lung cancer cases, depending on regional indoor levels and smoking prevalence (WHO, 2009). Importantly, tobacco use amplifies radon’s effect: smokers exposed to elevated radon levels face up to 25 times the lung cancer mortality risk compared to non-smokers (U.S. EPA, 2003).

**Occupational Evidence from REE Miners**

Significant occupational health effects have been documented among workers in REE mining. A landmark cohort study at China’s Bayan Obo mine, a combined rare earth and iron operation reported elevated lung cancer mortality among 3,000 workers exposed to thorium-rich dust and radon/thoron progeny. The standardized mortality ratio (SMR) for lung cancer was 6.13, compared to 1.90 in local controls, with 27 observed deaths against 8 expected by 2001 (Chen and Chen, 2008). These findings remained statistically significant even after adjusting for smoking status and represent some of the first direct evidence implicating thoron exposure in occupational carcinogenesis.

**Community Health Implications**

Beyond the workplace, communities near REE mines may also face elevated radon exposure. In villages near Vietnam’s North Nam Xe deposit, outdoor radon concentrations reached 920 Bq/m³, more than three times the WHO-recommended action level of 300 Bq/m³ (Dung et al., 2015). Long-term health surveillance in the area documented increased incidence of respiratory illnesses, which researchers linked to chronic radon exposure from mine emissions (Nguyen et al., 2022). Although lung cancer remains radon’s most established health outcome, these findings highlight the importance of community-level monitoring and mitigation programs in REE-producing regions.

**Secondary Health Effects**

While the link between radon and lung cancer is well-documented, evidence for other health effects remains limited and inconclusive. Some studies have reported possible increases in respiratory infections, such as tuberculosis, and suggested potential genotoxic effects, including chromosomal aberrations in populations chronically exposed to radon and thoron (Nguyen et al., 2022; Chen and Chen, 2008). Although these outcomes may be confounded by other environmental exposures, they underscore the need for broader health surveillance strategies in REE mining communities.

**5. Exposure Pathways in REE Production Stages**

**Exploration and Development**

In the early phases of exploration, radon exposure is generally minimal unless boreholes intersect uranium- or thorium-rich formations. However, drill cuttings and core storage areas may locally accumulate hazardous levels of radon gas. During the mine development stage, especially in underground operations, tunneling into ore bodies releases radon into confined spaces. Without pre-operational ventilation and baseline radon characterization, early occupational exposures may go undetected representing a significant regulatory and safety oversight (Ault et al., 2015; IAEA, 2011).

**Mining Operations**

Underground Mining:

In underground mining, fractured ore bodies release radon gas into poorly ventilated adits and tunnels. This is particularly evident in China’s clay-hosted REE operations, where radon levels have approached those seen in uranium mines. Radon concentrations ranging from 11 to 19,600 Bq/m³ have been reported in rare earth–associated underground metal mines (IAEA, 2015). One study documented an average annual dose of 1.41 mSv in a rare earth mine in Inner Mongolia, with 53 percent attributed to thoron (²²⁰Rn) (IAEA, 2015). Workers face high exposure during blasting and drilling phases. In the absence of regulatory mandates, radiation dosimetry is often lacking or inconsistently applied (Talan and Huang, 2022; Lewis, 2016).

Open-pit Mining:

Open-pit REE mines benefit from ambient ventilation, but radon can still accumulate in enclosed spaces such as crushing facilities, storage rooms, or pit walls with limited air movement. At the Nam Xe rare earth deposit in Vietnam, radon concentrations have been reported between 6.7 and 465 Bq/m³. At China's Bayan Obo open pit mine, radon levels have exceeded 2,500 Bq/m³ in localized areas, and thoron concentrations have averaged around 1,000 Bq/m³, with some measurements exceeding 6,000 Bq/m³. These findings highlight that even surface mining operations can pose significant airborne radiation exposure risks under certain conditions (Chen and Chen, 2008).

**Beneficiation Processes**

The beneficiation stage, including crushing, grinding, and screening substantially enhances radon release by increasing the ore’s surface area and diffusion potential. Workers are exposed to both free radon gas in enclosed buildings and alpha-emitting progeny (e.g., polonium-218) attached to airborne dust. Tailings derived from monazite-rich ores are particularly problematic due to their high radium content, which produces sustained radon flux. Effective mitigation often requires wet slurry tailings management to suppress airborne emissions (IAEA, 2015; Barakos et al., 2016).

**Chemical Processing**

In chemical separation facilities, processes such as acid baking and leaching occur in closed systems, but radon and thoron can concentrate within equipment. Worker exposure often occurs during maintenance or unplanned leaks. Residues such as thorium-bearing filter cakes can account for over 70% of total plant radiation dose, as shown in operational studies in Egypt (El Afifi et al., 2017). Additionally, intermediate liquids or sludges may concentrate radioactive progeny, increasing risks for staff involved in downstream processing and waste handling.

**Waste Management and Community Exposure**

Tailings and residues from REE extraction represent persistent sources of radon. Dry-stacked tailings emit radon directly into the atmosphere, while submerged or ponded wastes can release radon through degassing of surface water. The U.S. EPA's radon flux benchmark of 20 picocuries per square meter per second (20 pCi/m²·s), applied to uranium tailings, does not apply to REE operations even if their tailings contain comparable levels of thorium or radium (EPA, 2016; Ault et al., 2015). Thorium-rich residues, such as those from Lynas’ Malaysian refinery, require engineered containment systems to prevent long-term emissions. Furthermore, cases of radioactive mine waste being reused as construction aggregate pose severe, delayed health risks to nearby populations.

**Pathway Synthesis**

Radon exposure in the REE lifecycle is both stage-specific and multi-pathway. Occupational risks are highest in enclosed or poorly ventilated environments such as underground mines, beneficiation areas, and residue storage facilities. In contrast, community exposure arises mainly from long-lived tailings and poorly managed waste reuse. Effective control strategies must therefore be tailored to each production phase: ventilation and monitoring in mines, closed-loop systems and off-gas treatment in processing plants, and long-term engineered containment for all radon-emitting residues.

**6. Regulatory Frameworks and Policy Gaps for Radon in REE Industries**

**International Guidelines**

The International Atomic Energy Agency (IAEA) defines workplace radon exposure as an “existing exposure situation” and recommends a reference level of 1,000 Bq/m³, above which remedial action should be taken (IAEA, 2015). The International Commission on Radiological Protection (ICRP) advocates for even stricter limits based on a 10 mSv/year dose constraint (Pushparaja, 2017). The European Union mandates a threshold of 300 Bq/m³ under Directive 2013/59/Euratom (IAEA, 2015). However, none of these international frameworks explicitly address radon in the context of rare earth element (REE) operations. The absence of REE-specific guidance enables regulatory inconsistencies, with some jurisdictions failing to recognize REE mines as radiologically significant operations requiring uranium-level controls.

**United States: Regulatory Fragmentation**

In the U.S., regulatory oversight of radon hazards in REE operations is fragmented across several federal agencies. The Environmental Protection Agency (EPA) regulates radon emissions from uranium tailings under a 20 pCi/m²·s flux limit, but this standard has not been extended to rare earth facilities (Fuente et al., 2023). The Occupational Safety and Health Administration (OSHA) still enforces a 100 pCi/L (~3,700 Bq/m³) radon exposure limit over a 40-hour workweek—a legacy standard that remains unchanged despite advances in radiation health science (Lewis, 2016). The Mine Safety and Health Administration (MSHA) applies ventilation standards to uranium mines but does not mandate radon-specific monitoring for REE operations (NRC, 1983). Meanwhile, the Nuclear Regulatory Commission (NRC) excludes unprocessed REE ores from its jurisdiction under 10 CFR Part 40, deferring oversight to individual states, many of which lack specialized radiological expertise (U.S. NRC, 1983). As a result, sites like the Mountain Pass mine operate under inconsistent state-level rules with no unified federal framework.

**China: Enforcement Challenges**

China, as the global leader in REE production, formally requires environmental impact assessments (EIAs) that include radiological reviews for mining projects. The country also applies a radon exposure limit of approximately 4 working level months (WLM)/year in uranium operations. However, implementation in the REE sector is inconsistent. While major facilities like Bayan Obo maintain some dust and radon control measures (Chen and Chen, 2008), illegal mining, particularly of ion-adsorption clay deposits in southern provinces has historically evaded regulatory oversight (Ault et al., 2015). Despite post-2010 enforcement campaigns, the lack of public reporting on radon levels limits independent evaluation of occupational health protections.

**Comparative Global Approaches**

Australia provides one of the most rigorous models for REE radiation oversight. Through ARPANSA, the country mandates radiation management plans for any mining site with combined uranium and thorium levels exceeding 1 Bq/g, along with routine worker dose monitoring. Ironically, this strict regulatory regime partially drove Lynas Corporation’s decision to relocate its processing operations to Malaysia, where oversight was initially more lenient. Following widespread public protests, Malaysian authorities introduced stricter regulations, including mandatory long-term waste disposal plans under IAEA review. In Africa, regulatory frameworks remain inconsistent. Only countries with uranium mining experience, such as Namibia apply comparable radon controls. The European Union enforces a 300 Bq/m³ workplace limit but still faces awareness gaps; during Greenland’s evaluation of the Kvanefjeld project, regulators initially underestimated radon risks specific to REE processing.

**Systemic Deficiencies**

Four systemic failures perpetuate radon risks across the REE industry. First, there is a lack of systematic monitoring. Few jurisdictions require radon surveillance at REE sites, and publicly available data remains limited. Second, enforcement capacity is weak. Inspectors often lack radiological training, monitoring equipment is inconsistently calibrated, and ventilation standards are poorly implemented. Third, stakeholder awareness is low. Workers are rarely provided with radon safety education, and local communities often lack information about exposure risks or available remediation measures. Fourth, regulatory frameworks prioritize hazard (geogenic radon potential) over risk (population exposure). Hazard-based approaches like Radon Priority Areas (RPAs) focus on high-radon zones but neglect population density, leading to inefficient risk reduction. For example, in Germany, 83% of buildings exceeding 300 Bq/m³ lie outside designated high-hazard zones due to urban density rendering such policies ineffective for reducing collective lung cancer burdens (Petermann et al., 2022)

**Conclusion of Regulatory Analysis**

The global regulatory approach to radon in REE mining remains fragmented and insufficient. Outdated exposure thresholds, inconsistent classification of REE activities under radiological law, and weak enforcement mechanisms contribute to a hazardous policy vacuum. Case studies from Malaysia (Lynas) and China (Bayan Obo) demonstrate how this regulatory gap can lead to real-world health consequences. To address these issues, REE mining and processing must be formally recognized as NORM activities and subjected to uranium-equivalent safeguards, including binding exposure limits and integrated monitoring programs.

**7. Conclusion and Policy Recommendations**

Rare earth elements are central to the global transition toward clean energy and digital innovation. However, their extraction and processing involve substantial, underappreciated radiological risks, primarily from radon and thoron emissions. Data from sites such as Bayan Obo demonstrate elevated lung cancer rates and broader respiratory health impacts among both workers and nearby residents. These findings underscore an urgent need to integrate REE-specific safeguards into national and international radiation protection frameworks.

**Modernizing Exposure Limits**

Regulatory bodies must adopt radon exposure limits grounded in current science. Legacy thresholds—such as OSHA’s 100 pCi/L (~3,700 Bq/m³) and MSHA’s 4 WLM/year—should be replaced by tiered, risk-based standards: 300 Bq/m³ for general occupational settings and 1,000 Bq/m³ for mining environments. These limits must be accompanied by mandatory ALARA (As Low As Reasonably Achievable) protocols and ventilation targets. In practice, ALARA in REE settings may involve controlled blasting schedules, localized ventilation systems near processing units, and regular monitoring to minimize airborne radon concentrations. Critically, exposure thresholds must be implemented within risk-based frameworks that account for population density, not just geogenic hazard. As Petermann et al. (2022) demonstrate, purely hazard-driven policies (e.g., Radon Priority Areas) avert <1% of radon-attributable lung cancers when focused solely on high-hazard zones, underscoring the need for nationwide strategies. Such reforms would align national policies with ICRP and WHO models and directly address the observed 16% increase in lung cancer risk per 100 Bq/m³ of chronic radon exposure (IAEA, 2015).

**Integrating REEs into Radiation Protection Frameworks**

Rare earth facilities must be formally recognized as radiologically significant under national radiation protection laws. For example, Australia mandates radiation management plans and regulatory oversight through ARPANSA for any mining operation with uranium or thorium concentrations above 1 Bq/g, thereby formally integrating REE facilities into its national radiation protection framework (IAEA, 2011).

This requires licensing of operations that exceed uranium or thorium threshold concentrations, routine radon and gamma monitoring, and the presence of certified radiation safety officers at large-scale sites. The IAEA should issue dedicated REE guidance documents to close jurisdictional ambiguities and ensure that NORM protocols are extended across all processing stages—including transnational supply chains.

**Ensuring Monitoring Transparency**

Transparent, real-time monitoring should be mandatory across all high-exposure zones, including underground mines, crushing facilities, chemical reactors, and waste storage areas. Data should be routinely shared with both regulators and workers. Publicly accessible environmental reports that include boundary radon concentrations and tailings emission rates help foster community trust and enable timely interventions when levels approach action thresholds. In uranium mining, for example, some jurisdictions employ digital dashboards and continuous detectors to flag exceedances and initiate ventilation adjustments, offering a potential model for REE operations (Barakos et al., 2016).

**Prioritizing Stakeholder Education**

Worker education must become a regulatory requirement. Training should cover safe work practices in radon-prone areas, proper respirator use, and the role of ventilation in exposure control. Concurrently, companies must engage in structured community outreach, offering information about exposure pathways, radon testing, and mitigation options. Such programs are essential to address local concerns especially in light of past controversies, such as those surrounding the Lynas facility in Malaysia.

**Implementing Long-Term Health Surveillance**

Post-closure monitoring of tailings sites must continue for decades and should be supported by financial assurance mechanisms to fund long-term stewardship and verify the effectiveness of radon suppression infrastructure. While international agencies such as the IAEA and OECD-NEA recommend such financial guarantees, their implementation remains inconsistent and is typically left to national regulatory frameworks (IAEA, 2011).

**Fostering Global Cooperation**

The IAEA, ILO, and allied organizations should establish a dedicated task force to harmonize REE radon standards, facilitate best-practice sharing, and assist emerging producers with technical and regulatory capacity. Harmonization efforts must abandon purely hazard-driven models, as low-hazard urban areas may contribute disproportionately to collective risk due to population density, a pattern observed in the EU and likely transferable to REE-producing regions (Petermann et al., 2022). While these agencies do not enforce national policies, they possess the infrastructure and mandate to support harmonized guidance, capacity-building, and technical assistance. Programs must train inspectors, supply monitoring tools, and strengthen local enforcement frameworks. Without international cooperation, regulatory arbitrage will continue to shift radiological risk toward nations with the weakest safeguards.

**Concluding Imperative**

Bridging the current policy gaps requires that rare earth operations receive radiological oversight on par with uranium mining. Science-based limits, real-time surveillance, long-term health monitoring, and community engagement must become standard practice. These interventions, along with the agencies best positioned to lead them, are summarized in Table 1. By embedding these protections now, the REE industry can grow sustainably without compromising the health of workers or communities. The moment for action is urgent, as today's regulatory inertia risks hardwiring future disease burdens into global clean energy supply chains.

**Table 1.** Summary of Key Recommendations and Responsible Authorities

| **Policy Recommendation** | **Responsible Authority** |
| --- | --- |
| Set risk-based radon exposure limits | National radiation protection agencies; IAEA |
| Implement real-time radon surveillance | Mining and processing companies; Environmental regulators |
| Establish long-term health monitoring programs | Ministries of Health; Public health institutions |
| Ensure community engagement and transparency | Local governments; Civil society; REE operators |
| Regulate REE sites under radiological frameworks | National regulators; ARPANSA, IAEA |

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