Technical Report
on
Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining

Volume 1:

Mining and Reclamation Background

U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
Radiation Protection Division (6608J)
1200 Pennsylvania Avenue
Washington, DC 20460

Previously published on-line and printed as Vol. 1 of EPA 402-R-05-007, January 2006
Updated June 2007 and printed April 2008 as EPA 402-R-08-005

Acknowledgments

This report was prepared by the U.S. EPA, Office of Radiation and Indoor Air, Radiation Protection Division, Ariel Rios Building, 1200 Pennsylvania Avenue, N.W., Washington, DC 20460. The draft text was distributed for review to the EPA's Regional Radiation program managers of EPA's Regions I through X. It was also sent to the membership of EPA's National Hard Rock Mining Team and Abandoned Mine Lands Team, who are employees of the following EPA offices: U.S. EPA Regions I through X, U.S. EPA Office of Solid Waste and Emergency Response, U. S. EPA Office of Water, U.S. EPA Office of Compliance and Enforcement, and U.S. EPA Office of Research and Development. Comments from those reviewers were incorporated into a revised draft which then underwent peer review and outside review by external organizations and individuals. EPA would like to thank the following external reviewers: Dr. Thomas Gesell, Idaho State University, Dr. John Price, Nevada Bureau of Mines and Geology, and William Chenoweth. EPA is especially appreciative of the comments provided on the draft by the members of the Interagency Steering Committee on Radiation Standards, NORM Subcommittee, as well as the U.S. Nuclear Regulatory Commission, Dr. James Otton of the U.S. Geological Survey, plus the National Mining Association and several of its member companies, and the Wyoming Mining Association. The comments of all reviewers were carefully considered and incorporated, wherever possible, throughout the revised report.

The final report and its earlier drafts were prepared with the active participation of the following EPA employees:

Sanjib Chaki
Elliot Foutes
Shankar Ghose
Brian Littleton
John Mackinney
Daniel Schultheisz
Mark Schuknecht
Loren Setlow
Behram Shroff
Thomas Peake

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Executive Summary

This report, the first of two volumes, examines the occurrence of uranium in its natural settings in the United States, its industrial uses, and the methods employed over the last century to extract it from ore deposits. In addition, the report explores the nature of solid and liquid wastes generated by the extraction methods, and the various reclamation and remediation methods which can environmentally restore the extraction site. A second volume, to be issued separately, will examine, in a general way, the potential radiogenic cancer risks from abandoned uranium mines, as well as environmental and geographical issues associated with those mines. The intent of that report will be to generally identify who is most likely to be exposed to uranium, and where the greatest risks may be found. U.S. Environmental Protection Agency (EPA) field studies are used in both reports, providing examples of current conditions of abandoned and remediated mines. A related report compiles information from multiple sources providing locations throughout the United States, though concentrating on sites of the western U.S., that have been explored or mined for uranium.

In this report, Naturally Occurring Radioactive Material (NORM) is defined as: **Materials which may contain any of the primordial radionuclides or radioactive elements as they occur in nature, such as radium, uranium, thorium, potassium, and their radioactive decay products, that are undisturbed as a result of human activities.** The term Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) is defined as: **Naturally occurring radioactive materials that have been concentrated or exposed to the accessible environment as a result of human activities such as manufacturing, mineral extraction, or water processing.** Technologically enhanced means that the radiological, physical, and chemical properties of the radioactive material have been altered by having been processed, or beneficiated, or disturbed in a way that increases the potential for human and/or environmental exposures.

EPA's Radiation Protection Division decided that a further review of the current hazards associated with uranium mining TENORM was warranted following a review of EPA's guidance for TENORM by the National Academy of Sciences (NAS), EPA's response to the NAS study, and discussions with EPA's Science Advisory Board (SAB). The SAB agreed with EPA's intent to make TENORM documents useful to a broad audience, but also recommended that the whole life cycle of a TENORM source, in this case uranium extraction, be considered beyond regulatory or inter-agency considerations, and that the impacts of non-radiological contaminants also be examined.

In addition to most sources of TENORM, EPA has authority for environmental standard setting under the Uranium Mill Tailings Radiation Control Act, cleanup of hazardous waste sites which currently include some former uranium mines, and assistance to Native Americans that has also included environmental reviews of proposed *in situ* leaching (ISL) facilities. This document will provide limited background materials on uranium milling and ISL operations and waste generated by those processes, even though they are considered to be byproduct materials, not TENORM, under the Atomic Energy Act and its amendments. Information will also be provided on the regulatory agencies responsible for oversight of those operations.

Uranium mills and mill tailings impoundments are regulated by the NRC or its Agreement States. Many of the physical and chemical processes used at uranium mills are the same as those which extract uranium at ISL operations. While the tailings are not legally considered TENORM in the United States, this phase of the uranium fuel cycle is described in the report, in part, because radiation protection standards for the tailings impoundments may have applicability to waste disposal for uranium mine TENORM wastes. Additionally, the NRC has decided to allow mill operators to dispose of wastes other than tailings in the impoundments. This may be a possible disposal route for some currently unreclaimed conventional uranium mine TENORM.

Uranium in ores can be extracted and chemically converted into uranium oxide (U_3O_8) or other chemical forms usable in industry. Uranium-238 undergoes radioactive decay into a long series of 13 different radionuclides before finally reaching a stable state in lead-206. These radionuclides each emit alpha or beta radiation and some also emit gamma radiation. Some of these progeny radionuclides are highly radioactive and can pose significant human health risks. One of those radionuclides in the series is actually a radioactive gas, radon-222. The most significant applications of uranium have been for nuclear weapons production and electric power generation. Concurrent with these efforts to develop weapons and harness atomic energy for electricity, the surging demands for uranium led to an exploration and mining boom for the mineral commencing in the late 1940s and ending in the 1980s, with a continuing decline until about 2004. An increase in all aspects of the industry since then included drilling, mining, production and employment.

Most uranium mining in the United States has taken place in the Colorado Plateau region including the states of Utah, Colorado, New Mexico, and Arizona, though more than a dozen states have hosted uranium mining operations. Some mines were focused on extraction of just uranium minerals, whereas many other mines produced uranium along with other valuable minerals found together in the same ore.

Mining is the mechanical process by which mineral ores are extracted from the earth. The term ore implies economic viability in which the value of the metal extracted from the host rock is worth more than the total costs of extraction and site restoration. Protore is mined uranium ore that is not rich enough to meet the market demand and price. This subeconomic ore is often stockpiled at the mine site for future exploitation under the appropriate economic or market demand conditions. A significant waste material that is classified as TENORM from uranium mining is overburden. Overburden overlies the uranium ore body, but is not necessarily enriched in uranium as is protore. Other mine wastes which could be classified as TENORM include unreclaimed subeconomic ores (protore), waste rock (which is rock void of uranium ore which may have been set aside as waste after removal of top-soil, overburden and uranium ore or veins), drill core and cuttings, and mine and pit (or pit lake) water.

Early mining methods for uranium used what are termed conventional methods: open-pit mining is employed for ore deposits that are located at or near the surface, while underground mining is used to extract ore from deeper deposits. The early small mining endeavors generated small quantities of waste typically discarded within a few feet to hundreds of feet (100 meters or more) of the mine opening or pit. Generally, tens to hundreds of acres (or hectares) may be covered by overburden and waste rock at surface mining sites. This study found that the surface area affected by major underground mining activities generally involves less than about 50 acres (20 hectares).

The volume of waste produced by surface, open-pit mining is a factor of approximately 45 greater than from underground mining, based on their respective averages. Thus, the amount of overburden generated from open-pit mines far exceeds that of underground mines. The U.S. Geological Survey estimated that the total amount of waste rock generated by the approximately 4,000 operating conventional mines in their data files is between one billion and nine billion metric tons of waste, with a likely estimate of three billion metric tons. The characteristics of overburden and waste rock from conventional mines depend on the geology of the zone where the ore was originally mined, and how the waste was subsequently treated. Overburden and waste rock can include huge boulders that may have been broken down with explosives and heavy machinery into particles as small as clay size.

Increased use of ISL as an “unconventional”, though now relatively common, mining method, has significantly reduced the volume of solid waste generated (regulated by the NRC or its Agreement States). The solid waste from ISL consists of: (1) soil and weathered bedrock material, (2) waste from drilling of injection and production wells, and (3) solids precipitated during storage and processing of fluids in holding ponds. The total areal extent of an ISL operation may be large, covering from 200 to more than 6,000 acres (81 to 2,430 hectares), depending on how drill holes are situated, and how extensive evaporation ponds are, though the facilities themselves may take up only a small part of the total acreage. Available data are insufficient to estimate the total amount of solid and liquid wastes generated by existing and previous ISL operations.

Radiation and hazardous materials studies from mine reclamation assessments indicate that material identified as “waste” or “overburden” varies widely in radium-226 activity, but that for most waste piles dominated by overburden material, measurements higher than 20 pCi/g (0.74 Bq/g) are unusual. Protore, on the other hand, can be considerably higher in radium-226 activity, with most material in the range of 30–600 pCi/g (about 1–22 Bq/g). As a point of comparison, information on radionuclides present in ISL operation wastewater ponds is very limited. Liquid wastes from those operations have some residual uranium and radium-226 activities that range from background levels (<2 pCi/L) to concentrations as high as 3,000 pCi/L (111 Bq/L). Solid wastes from ISL operations can have several hundred ppm uranium and 300–3,000 pCi/g radium-226 (about 11–111 Bq/g).

Radon measurements in some abandoned underground mines where mechanical ventilation has ceased are quite high, and pose risks for prolonged human exposure by members of the public visiting for recreation, exploration of old workings for geologic purposes, or reclamation workers. As an example, radon readings by alpha track canisters installed at underground mine portals of the Ross Adams uranium mine in Alaska measured from 212 pCi/L to 540 pCi/L (about 8 to 20 Bq/L). Radon emanation coefficients (the fraction of radon atoms present in a material that emanate into rock or sediment pore space) for sandstone and other uranium ores are extremely variable. Coefficients vary with: (1) uranium mineralogy; (2) radium mineralogy; (3) host rock lithology; (4) grain size of uranium/radium minerals; (5) comminution, or fineness, of the ore; (6) estimated porosity and permeability of the ore; (7) moisture content; and (8) ore grade. Unlike barren or low-activity waste rock, waste rock and protore piles with elevated activity not only form more radon, but in many districts they release a great deal of that radon to pore spaces, and the radon is free to migrate.

Radon flux rates from overburden are difficult to characterize because of the rock’s diverse physical forms and matrices, and diverse emplacement and disposal methods. Field measurements indicate that average radon flux rates vary from about 2–60 pCi/m^{2}s (about 0.07–2 Bq/m^{2}s) for overburden materials to as high as a few hundred pCi/m^{2}s (> about 7 Bq/m^{2}s) for low-grade ore materials. The broad range of radon flux rates is due, in part, to varying radium concentrations (the parent radionuclide) found in protore that is at times disposed of with overburden. Radon flux rates much higher than these wastes have been reported for undisturbed natural rock outcrops adjacent to uranium extraction operations.

Elevated gamma radiation is always found at uranium mine sites. The primary contributors to gamma exposure are the decay products of radium; the higher the radium present, the higher the ultimate gamma exposure rate. Radium content is also roughly proportional to uranium content in raw mine materials. Exposure rates associated with ambient background levels range from 10 to 85 μR/hr, averaging about 20 μR/hr including background. Protore exposure rates range from 80 to 1,250 μR/hr, with an average value estimated at 350 μR/hr.

A number of heavy metals may occur in association with uranium deposits and wastes from uranium mining. Heavy metals on site, particularly arsenic, can be of concern, and can pose serious risks if they migrate to groundwater. Depending on local geology and climate, the presence and eventual leaching or remobilization of these metals could lead to contamination of surrounding lands and water bodies. Waters affected by uranium mining may be on, adjacent to, or at some distance from a mine or mines. Uranium and thorium, and radium to a lesser extent, can be mobilized by either acidic or alkaline solutions. Pyrite and other sulfur-bearing minerals are key determinants as to whether acid mine drainage occurs. Most of the mines located in the sedimentary sandstone deposits of the southwestern United States are not in pyritic formations (with the exception of ores in South Texas, where pyrite and its pseudomorph, marcasite, are common), and the resulting runoff waters or pit lakes are generally neutral to alkaline in character (pH of 7 or higher). However, this contrasts with the measurements made at mine locations in the Pacific Northwest—areas with higher-than-average rainfall amounts and metamorphic and igneous rocks, including sulfur-bearing minerals that could transform runoff into acidic waters (pH < 7).

Mining reclamation is the act of returning a mine to a long-term stable condition, or its original contour, to ensure the safe reuse of the site by both current and future generations. When possible, a reclamation plan aims to return the affected areas to previously existing environmental conditions. Differing views as to what is an acceptable environmental condition for reclaimed mining sites explain the varying regulatory requirements for uranium mining sites. The existence of bonding requirements and/or financial guarantees in the cases where private parties are involved in the mine may also play an important role in determining the extent of reclamation. Extraction facilities licensed by the NRC or its Agreement States are required to have bonds sufficient to allow a third party to reclaim the property should the company holding the site fail. Additionally, regulatory requirements affect selected reclamation techniques, as some techniques may be adequate to meet less stringent requirements, but will not be suitable for more restrictive requirements. In some cases, the remoteness and aridity of a site and reduced risk for human exposure may affect decisions on whether a site is in need of reclamation, or the extent to which it is reclaimed, if at all.

Many site factors can influence the reclamation of a mining site, including topography, geology, hydrology, hydrogeochemistry, climatology, ecology, operating characteristics, radiological characteristics, and socioeconomic characteristics. For example, the topographical setting (whether the site is located in a valley or on a hillside) can affect a site's hydrology and climate. Knowledge of a site's climatology, hydrology, and hydrogeochemistry is needed for assessing its impacts on water bodies in the area. In turn, these impacts may influence decisions on strategies and techniques for reclamation.

A site's operational and radiological characteristics are of prime importance in its reclamation. The historical type of mining, mine layout, and extraction methods will affect the location and types of wastes present, and knowledge of how the mine operated can improve reclamation procedures utilized. Geotechnical aspects of the mine, including its stability, will help determine if certain reclamation options will endanger the workers, while radiological and chemical characteristics determine how much reclamation must be conducted. Off site characterization is extremely important too, as both natural and human factors may have resulted in dispersion of dusts, rock, liquid, refuse or other wastes contaminated with radionuclides or other pollutants beyond the borders of a mine or its related facilities. Transport of ore and waste rock to other locations away from a mine are not uncommon. In this regard, reconnaissance walking, aerial, and radiation surveying may provide initial evidence of the need for more detailed evaluations. Sampling of water and soils off site may also provide evidence of contaminant releases.

Treatment of contaminated mine wastewater is usually required, with release concentrations of specific contaminants dictated by federal and state requirements. While many treatment technologies are capable of achieving concentrations that are well below regulatory requirements, the accumulation of contaminants in the sediments may also need to be taken into account. Traditionally, large volumes of contaminated water being pumped or released from a site (greater than 1,500 ft^3/hr (42.5 m^3/hr)) are usually treated by some form of chemical process, though it may also be treated by newer technologies, such as biological treatment in wetlands, evaporation ponds, and reactive barriers. The residues and sludges from the treatment must be disposed of as determined by the state, federal, or Tribal land management agency. This can occur either on-site or at an engineered low-level radioactive waste disposal cell, or an approved off-site disposal area. In some cases, depending on the quality of remediated water, standing bodies of water may be left behind permanently.

EPA groundwater protection standards issued under authority of UMTRCA are required to be followed by ISL licensees of the NRC or its Agreement States. Remediation of groundwater in the wellfield must be conducted to return the groundwater and other systems to as close to pre-extraction conditions, or EPA drinking water maximum contaminant limit levels where possible or practical. If that is not possible, alternate concentration limits (ACL's) in terms of the presence of metals, organics, pH level, and radioactivity, may be approved by the NRC or its Agreement States, with EPA concurrence. In addition to those requirements, ISL operators also must comply with EPA Underground Injection Control regulations. Groundwater restoration is accomplished through a strategy called pump and treat. After an ISL wellfield is exhausted, the aquifer must be restored. During aquifer restoration operations, relatively large volumes of wastewater are generated. Waste disposal systems at ISL operations usually consist of a combination of evaporation ponds, deep-well injection, and surface discharge (usually via irrigation). Evaporation ponds must be double lined and must incorporate leak-detection and collection systems. Pond residues must be shipped off site to approved disposal facilities. Regulations prohibit the injection of ISL waste into aquifers containing less than 10,000 ppm of total dissolved solids. A variety of aquifer restoration processes have been used in the United States. Remediation generally follows five stages: (1) groundwater sweep, (2) water treatment, (3) reductant addition, (4) circulation, and (5) stabilization.

Reviews are provided in Chapter 4 of the report of the principal methods of reclaiming open-pit and uranium mines, including means of remediating releases of radionuclides, metals, or other hazardous materials on, and off-site. A discussion is also provided of the principal regulatory and other guidances issued by EPA, the NRC, and DOE for managing radiation at uranium mills and their tailings impoundments, closure of uranium extraction facilities, cleanup of radioactively contaminated soils, and protection and cleanup of groundwater sources from contamination from uranium mines and extraction facilities.

Data from a Department of Energy/Energy Information Administration study reveal that the costs of reclamation without site monitoring for 21 mines ranged from a low of $2,337/hectare of disturbance to a high of $269,531/hectare of disturbance. The average total estimated cost is $13.9 million per mine. Many smaller mines less than 25 acres (10 hectares), which may constitute the majority of currently unreclaimed mine-scarred lands, especially in arid regions, may require remediation costs on the order of $45,000 or less. This cost would be incurred to bury waste piles back in a pit or underground mine opening, clean up the soil to lower radionuclide and metal levels, and close or armor the mine opening with rock. Remediation actions under CERCLA for spilled ore off-site of a mine can be expensive. U.S. DOE/EIA in 1995 estimated average decommissioning costs for ISL operations were an estimated $7 million. On the other hand, cleanup in 2005 of 12 sites where ore had spilled off of ore trucks on the haul road between the Midnite Mine and the Dawn Mill in Washington state, some 18 miles distant, amounted to a cost of approximately $357,500.

When mining or extraction facilities are closed, stewardship and monitoring may or may not be required to ensure that remediation goals have been met. This requirement depends on statutory requirements for federal, state or Tribal agencies, the nature of the site, and local site conditions. For example, after the stabilization monitoring phase at NRC or Agreement State licensed/permitted ISL facilities, if there is no indication of increasing levels of groundwater constituents of concern, the site is released for unrestricted use. Conversely, mines remediated under EPA Superfund oversight, can require open ended periodic monitoring until it is similarly determined that the site can be released. Many mines on federal, state, and Tribal lands in the western U.S. have been considered closed without need for further monitoring once they have been reclaimed (or remediated if necessary). Uranium mill tailings sites under UMTRCA requirements once reclaimed are licensed to the DOE and designed for 1,000 years of control.

Overall, this report provides technical information on uranium mining, the associated TENORM wastes, and impacts from production. In addition, information is presented on reclamation and remediation considerations and technology used to facilitate the appropriate management of radiation and waste materials at both uranium mines, and uranium extraction facilities.