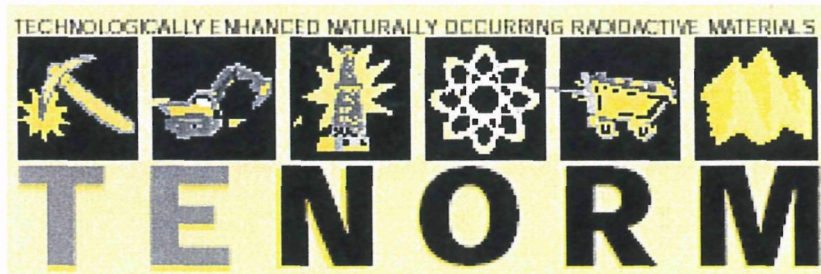# Technologically Enhanced Naturally Occurring Radioactive Materials From Uranium Mining

Volume 1:
Mining and Reclamation Background

Volume 2:
Investigation of Potential Health, Geographic, and Environmental Issues of Abandoned Uranium Mines

TECHNOLOGICALLY ENHANCED NATURALLY OCCURRING RADIOACTIVE MATERIALS

TENORM

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

Volume 1:

Mining and Reclamation Background

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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.

Chapter 1. Introduction

Uranium is a common element in nature that has for centuries been used as a coloring agent in decorative glass and ceramics. Uranium and its radioactive decay products are ubiquitous in nature, and contribute to natural background radiation found everywhere. In fact, it is important to note that many of the natural occurrences of uranium present radiation hazards without any disturbance from miners. By far, the greatest uses of uranium have been defense and electric power generation. The advent of nuclear weapons and nuclear power in the United States resulted in a full-blown exploration and mining boom starting immediately after World War II, making uranium the most important commodity in the mining industry. The uranium production peak spanned from approximately 1948 to the early 1980s (U.S. DOE/EIA 1992). Some uranium mining continues in the United States, and relatively high-grade resources in other parts of the world are being mined to meet continued demand. Through the first half of 2005 the industry had generated over 358,000 metric tons (MTs) of uranium (U_3O_8) to foster U.S. dominance in nuclear weapons technology, and later to feed the growing number of commercial power plants that utilized the enormous energy contained in the uranium nucleus.[1]

Another legacy of uranium exploration, mining, and ore processing were many unreclaimed land workings left behind where the uranium concentration in rock was either found or thought to be economically recoverable. Thousands of miners and prospectors, as well as large mining companies, searched the United States for mineral deposits concentrating the valuable metal, echoing the California gold rush 100 years earlier. In many instances before the 1970s, they left behind unreclaimed and exposed wastes elevated in radioactivity from uranium and its radioactive decay progeny, potentially exposing people and the environment to its hazards.

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.** Radiation levels presented by NORM are generally referred to as a component of "natural background radiation".

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. This definition differs somewhat from other definitions provided by the National Academy of Sciences (1999a) and the Conference of Radiation Control Protection Directors (CRCPD 2004) in that it further amplifies the need to include materials which have not been modified by human activities, yet have been disturbed in such ways that they can be misused by humans, or affect the environment[2]; it does not include a

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[1] Data compiled from U.S. DOE/EIA 2003a, 2003b, 2005b.

[2] The National Academy of Sciences (1999a) defined TENORM as "…any naturally occurring radioactive materials not subject to regulation under the Atomic Energy Act whose radionuclide concentrations or potential for human exposure have been increased above levels encountered in the natural state by human activities." The International Atomic Energy Agency (2003), although referring to this class of wastes and products as "NORMs", defined them as encompassing "all naturally occurring radioactive materials where human activities have increased the potential for exposure in comparison with the unaltered

reference to Atomic Energy Act materials as the definitions are changing (see further below and Appendix VI).

Under the Atomic Energy Act, the U.S. Nuclear Regulatory Commission (NRC) regulates operations which produce and concentrate uranium and thorium. In accordance with terminology of the Act, the NRC has defined in 10 CFR 40.4 "source materials" **as (1) uranium or thorium, or any combination thereof, in any physical or chemical form or (2) ores which contain by weight one-twentieth of one percent (0.05%) or more of: (i) uranium, (ii) thorium or (iii) any combination thereof. Source material does not include special nuclear material.** It also defines the "by-product materials" (wastes) of those operations **as tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes. Underground ore bodies depleted by such solution extraction operations do not constitute "byproduct material" within this definition.** Byproduct materials are also regulated by the NRC.

However, certain types of waste from conventional mining of uranium (surface and underground mining) are not subject to NRC regulation, and are considered to be TENORM. Thus, while this report includes information about uranium extraction, processing methods and wastes, only the wastes from conventional mining are considered to be TENORM, and subject to U.S. Environmental Protection Agency (EPA) and State agency oversight. Those distinctions will be made clear below, and elsewhere in this report.

Under the Energy Policy Act of 2005, the Atomic Energy Act was amended to place additional discrete (highly radioactive in small quantities) sources of TENORM under NRC jurisdiction which had the potential for use in a radioactive weapon. The definition of byproduct materials was further modified to include discrete sources of radium-226, any material made radioactive by use of a particle accelerator for use for a commercial, medical or research activity, or materials which might pose a similar threat if used to make a radioactive weapon. Specific requirements were provided for determining the appropriate waste disposal methods for these materials. The NRC regulatory definitions of byproduct materials to accommodate these amendments have not been revised to reflect the recent amendments as of this writing. While these products and wastes are not the subject of this report, further discussion on these changes to the Atomic Energy Act are included in Appendix VI.

Other important acronyms and definitions of key terms in this report can be found in Appendix I.

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situation. Concentrations of radionuclides (i.e. TENORM) may or may not have been increased." Alternatively, the Conference of Radiation Control Program Directors (CRCPD 2004) has defined them as a naturally occurring radioactive material whose radionuclide concentrations are increased by or as a result of past or present human practices. TENORM does not include background radiation or the natural radioactivity of rocks or soils. TENORM does not include "source material" or "byproduct material" as both are defined in the Atomic Energy Act of 1954, as amended (AEA 42 USC §2011 *et seq.*) and relevant regulations implemented by the NRC. EPA believes the definition should include materials which were disturbed, but not further concentrated by human activities; by not including this slightly broader definition, not only a significant amount of radioactive waste, but nearly all products which include TENORM would be exempted from regulation.

Previous EPA Reports

The U.S. Environmental Protection Agency has previously issued reports on the uranium mining industry in response to congressional mandates and programmatic needs. In 1983, EPA published its *Report to Congress on the Potential Health and Environmental Hazards of Uranium Mine Wastes* (U.S. EPA 1983 a, b, c), as required by the Uranium Mill Tailings Radiation Control Act of 1978. This study provided an important overview of the characteristics and generation of uranium mining TENORM wastes during a period when the uranium mining industry was still near its production peak. A subsequent 1985 *Report to Congress on Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale* (U.S. EPA 1985), carried out pursuant to requirements of the Resource Conservation and Recovery Act of 1976 (RCRA), as amended, provided additional risk information and characterization of uranium mining waste. In 1995, EPA issued the *Technical Resource Document: Extraction and Beneficiation of Ores and Minerals: Uranium* as a technical update to provide a means of evaluating wastes that were exempt from or subject to regulation under RCRA (U.S. EPA 1995a).

During the period 1989 to 1993, EPA worked on a draft scoping report (SC&A 1993), now out of print, which compiled information on TENORM in several industries, including uranium mining. A preliminary risk assessment was also developed for certain public and occupational exposure scenarios to the known radiation levels in those industries. Comments received on the draft from industry, as well as EPA's Science Advisory Board (U.S. EPA 1994), resulted in further revisions of the scoping draft, though it was ultimately decided that a final report would not be issued.

Following a review of EPA's guidance for TENORM by the National Academy of Sciences (NAS 1999a), EPA's response to the NAS study (U.S. EPA 2000b), and discussions with EPA's Science Advisory Board (SAB), EPA's Radiation Protection Division decided that a further review of the current hazards associated with uranium mining TENORM was warranted.

The SAB (U.S. EPA 2001d) 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 the Agency's technical reports. In addition to most sources of TENORM, EPA has authorities 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 included assistance in environmental reviews of proposed *in situ* leach (ISL) facilities. This report will provide limited background materials on uranium milling and ISL operations and waste generated by those processes, even though they may not be considered TENORM by virtue of their regulation 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, which is a possible disposal route for some currently unreclaimed conventional uranium mine TENORM.

This report is the first of two volumes on uranium mining TENORM. It provides background information on the occurrence, mining, and reclamation of uranium mines and mills. Chapter 1 examines the occurrence of uranium in nature, its uses, and its contribution to background radiation in the United States. Chapter 2 provides an overview of mining and milling methods used to extract uranium from its host rocks, while Chapter 3 provides an evaluation of the volume and characteristics of uranium mining TENORM wastes in the United States. Chapter 4 provides a process-oriented review of reclamation[3] and remediation[4] techniques and goals to clean up uranium mines and extraction facilities to reduce their hazards to the environment, while Chapter 5 summarizes the key information developed in the report. The second volume entitled *Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) from Uranium Mining: Volume II: Investigation of Potential Health, Geographic, and Environmental Issues of Abandoned Uranium Mines (2006a)*, will evaluate, in a general way, potential radiogenic cancer and environmental risks posed by abandoned uranium mines. A technical report entitled *Uranium Location Database* (EPA 2006b) in concert with these volumes will provide information on an EPA generated digital spatial database on mines with uranium, and mill locations.

Information on uranium mining waste characteristics for this report has been obtained from several sources, including industries, EPA contractors, federal, state, and Tribal agencies, and scientific literature published by various national and international organizations. EPA's own field studies on a number of uranium mining sites around the United States, several of which are described in the case studies of the Appendix, have contributed to a better understanding of the physical, geographic, and chemical aspects of these wastes. The draft of this report underwent an outside peer review following the Agency's peer review process, and was provided to member agencies of the Interagency Steering Committee on Radiation Standards (ISCORS) Subcommittee on NORM, as well as other selected knowledgeable individuals and organizations, for comment.

Based on reviewers' comments received on the draft reports as well as meetings with stakeholders, the Agency will make a determination on what further steps may be necessary for the purpose of radiation protection from this source of waste material. The specific wastes of EPA concern from this report and study are from conventional open-pit and underground uranium mines, and include overburden, unreclaimed subeconomic ores (protore), waste rock[5], core hole and drill cuttings, mine and pit (or pit lake) water.

As a result of the review comments, significant new information was added to the report on uranium geochemistry and radionuclide environmental transport, as well as on uranium mine, ISL, and mill tailings reclamation methods and requirements. Waste and mining terminology was made more consistent across the report, more definitions of geological, mining, and radiological terms were provided and also included as a glossary in Appendix I, the report tone was changed, and several new references and figures were added. New text was added to this chapter (see above) to clarify the reasons information is included in this report on ISL and milling operations, even though they are for the most part overseen by agencies other than EPA. Responding to

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[3] Reclamation is the restoration of mined land to its original contour, use or condition.

[4] Remediation is the cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a Superfund site or uranium mine or extraction facility, including those included under the Uranium Mill Tailings Radiation Control Act (UMTRCA).

[5] Rock void of uranium ore which may have been set aside as waste after removal of top-soil, overburden and uranium ore or veins. Waste rock is defined as barren or submarginal rock or ore that has been mined, but is not of sufficient value to warrant treatment and is therefore removed ahead of the milling processes.

reviewers' comments, we have clarified in each chapter where specific wastes described are not considered TENORM and are subject to other agency regulations, and have added a new Appendix (VI) which provides information on the regulatory authorities of the principal federal and other agencies which oversee various aspects of uranium extraction and production. Errors in fact and numbers cited which we could verify were corrected throughout the report. Uranium price trends and mine production and reclamation status/ownership information was also updated as of early 2006.

Origins of Uranium

Uranium has been around a long time. Cosmologists believe uranium was formed in supernovae billions of years ago. Uranium is a metal found in most rocks on Earth in concentrations of one to four parts per million. Uranium is in fact more abundant than gold, silver, mercury, antimony, or cadmium, and more or less as common as tin, cobalt, lead, molybdenum, and arsenic (CRC 1994). And contrary to popular perception that uranium is somehow far away and isolated in high-security facilities, traces occur almost everywhere—in plants, soil, rock, seawater, and animals (including humans).

The German chemist Martin Klaproth is credited with discovering uranium in samples of the mineral pitchblende in 1789. He named it for the planet Uranus, discovered only eight years prior. Uranium was first isolated as a metal in 1841 by Eugene-Melchior Peligot. French scientist Henri Becquerel is noted for (among other things) discovering the property of radioactivity while observing radiation from the highly radioactive decay progeny (called radium) closely associated in uranium-bearing rock (Ewing 1999).[6] While "discovered" in the late 18th century, uranium had nevertheless been used for many centuries as a colorant in glass and ceramics. Yellow-colored glass containing one percent uranium oxide has been found in Italy dating to 79 A.D. (CRC 1994).

Physical Nature of Uranium

Uranium, a naturally occurring element with the atomic number 92, contributes to low levels of natural background radiation in the environment. Uranium in ores can be extracted and chemically converted into uranium dioxide (UO_2) or other chemical forms usable in industry. When refined, uranium is a silvery-white metal with very high density—65 percent denser than lead (CRC 1994).

Uranium is found naturally as three different isotopes[7]: U-238, U-235, and U-234. Other isotopes can be synthesized (created by humans), but all uranium isotopes are radioactive to varying degrees. Almost all uranium as found in nature is the isotope U-238 (Table 1.1). While in this report, general reference to uranium will be to uranium in its natural isotopic proportion, unless otherwise stated, it should also be noted that these proportions are not in fact entirely fixed.

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[6] See Appendix II for uranium decay series.

[7] An isotope is a variant of an element (having the same number of protons) but a different number of neutrons in the nucleus. For example, uranium has 92 protons. But uranium-238 has 146 neutrons, and uranium-235 has 143 neutrons.

**Table 1.1. Percentage of Natural Abundance and Half-Lives[8]
of Uranium Isotopes by Total Weight**

Almost all uranium as found in nature is the isotope U-238.

Isotope	Natural Abundance (%)	Half-Life (years)
U-238	99.2740	4.47 billion
U-235	0.7200	700 million
U-234	0.0055	246,000

Source: Eisenbud and Gesell 1997.

Uranium-238 undergoes radioactive decay into a long series of 13 different radionuclides before finally reaching a stable state in lead-206. These radionuclides emit alpha or beta radiation and some also emit gamma radiation of widely varying energies. EPA's glossary of radiation terms[9], defines radioactivity as "*the process of undergoing spontaneous transformation of the nucleus, generally with the emission of alpha or beta particles often accompanied by gamma rays.*" Some of these progeny radionuclides are very radioactive and can pose human health risks. One of the radionuclides in the series is actually a radioactive gas, radon-222, while the others are all solids.

Uses of Uranium in Industry

Uranium has more uses than many people are aware of, though most of them are fairly esoteric (Table 1.2). By far, the greatest uses have been in nuclear weapons production and electric power generation. Uranium has the rare property of being "fissionable." Its nucleus can be split, or fissioned, and in the process, releases enormous amounts of energy (as well as significant volumes of highly radioactive by-products). This realization in the late 1930s and early 1940s led to a race by U.S. scientists to produce an atomic bomb during World War II. However, U-238, the predominant isotope, is only nominally fissionable—not enough so for a workable bomb. Of the three natural isotopes of uranium, U-235 is by far the most fissionable. (see Appendix II for uranium-235 (actinium) decay series. There have been reported occurrences of uranium deposits in Africa which underwent spontaneous nuclear fission, and which were detected based on discrepancies in the ratios of uranium isotopes present in the geological deposit (Meshik 2005).

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[8] A half-life is the time in which one-half of the atoms of a radioactive isotope decay into another nuclear form. Half-lives vary from less than a billionth of a second to billions of years. Also called the physical or radiological half-life. Isotopes with longer half-lives tend to be more stable and less radioactive.

[9] See on the Internet the following site: http://www.epa.gov/radiation/terms/termqr.htm#r .

Table 1.2 Multiple Industrial Uses of Uranium
Uranium has more uses than many people are aware of.

Types of Uranium	Industrial Uses
Primary Uses	
Uranium	Nuclear weapons production and electric power generation.
Lesser-Known Uses	
Uranium	For production of copper, nickel, and steel alloys to enhance specific properties. For dating the Earth by making calculations based on the rate of decay of uranium and the relative proportion of its stable progeny lead-206. Incorporated into dental porcelain used for false teeth to simulate the fluorescence of natural teeth (a relatively minor historical use).
Depleted uranium	For inertial guidance systems and gyro compasses. Armor piercing conventional munitions, tank armor, and nuclear waste casks.
Refined uranium metal	For production of high-energy X-rays.
Uranyl nitrate	As a colored glaze for porcelain and glass and for manufacturing pigments (this practice has more or less ceased in the United States).
Uranyl acetate	In dry-copying inks and as a reagent in chemistry.
Uranium salts	As mordants for dyeing silk and wool.
Compounds of uranium	For photographic toning, and staining and dyeing leather and wood.

Sources: NCRP 1987a; USGS 1973; U.S. NRC 2001.

To produce a functional uranium-based atom bomb, U.S. scientists needed a high concentration of the isotope U-235. With great difficulty and cost, they separated the natural uranium isotopes to increase the concentration of U-235 relative to U-238. This process is called enrichment, because the extracted fraction is enriched in U-235 (to 90 percent or more for bombs). The highly fissionable U-235 is also used to produce nuclear energy, but is typically enriched only to about three percent (U.S. DOE 2002).

In addition to fission, atomic nuclei, such as uranium, can undergo a process called neutron capture, which permits the generation of plutonium (Pu) isotopes. One of these, Pu-239, is even more fissionable than U-235 and has very high energy outputs. Plutonium is made by bombarding uranium-238 targets in specially designed reactors (Rhodes 1987).

The enrichment process produces huge quantities of remnant, depleted uranium that is almost pure U-238. Depleted uranium is very stable and very dense, has poor fission properties, and is only very weakly radioactive. Decades of uranium enrichment have generated enormous quantities of depleted uranium. The U.S. Department of Energy has over 500,000 metric tons (MTs) of surplus depleted uranium stored on site at two of its large enrichment facilities (U.S. DOE 2002).

The uses of and markets for depleted uranium are fairly limited and are typically unrelated to any nuclear properties. As such, its value is low. Perhaps the most notable use is in military munitions and armored shielding. Like many other metals (e.g., magnesium), uranium is pyrophoric, which means that it reacts quickly with oxygen. As a result, the rapid oxidation of small particles (which have a relatively larger ratio of surface area to volume) of uranium can generate sufficient heat to cause ignition. Consequently, due to this pyrophoric nature and high density, projectiles made of depleted uranium burn on high impact and penetrate enemy armored tanks with ease. As shielding, thick plates of depleted uranium effectively inhibit penetration from projectiles. Due to its high density, depleted uranium finds domestic application in the keels of yachts, as ship ballast, and as counterweights for control surfaces (rudders and elevators) in airplanes and

helicopters. Also because of their high density, depleted uranium blocks are used for shielding gamma radiation in research facilities.

Geology and Distribution of Uranium

The very large ionic size and chemical properties of uranium tend to allocate it to certain mineral assemblages, and lend to fractionation and concentration of uranium in particular rock types. Common uranium minerals include uraninite, coffinite, brannerite, carnotite, uranophane, autunite, pitchblende, and torbernite. Of these, uraninite (nominally UO_{2+x}) is the most widespread and significant economically, followed by coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$), and brannerite ($U^{4+}Ti_2O_6$) (Finch and Murakami 1999).

Most deposits of uranium in the U.S. were formed when oxidizing groundwater, which dissolves and transports uranium in a hexavalent[10] state, combines with carbonate, sulfate, and phosphate, and were subsequently reduced in their oxidation state by the presence of either organic matter or iron disulfide in the rock formations. If this occurred, uraninite or coffinite would have precipitated in a quadrivalent (four net positive ions) phase (Burns and Finch 1999). The inverse of this reaction (i.e., dissolution of uranium in mineral form) is used for ISL and hydrometallurgical processing of uranium (see Chapter 2), and introduction of bisulfide or hydrogen sulfide is a process used in aquifer restoration (see Chapter 4).

As a result of its size and charge, the uranium atom does not tend to fit well into typical igneous rock-forming minerals (such as feldspars, quartz, micas, amphiboles, pyroxenes, olivine, and titanomagnetite) and tends to be concentrated in silica-rich magmas such as rhyolites and granites (Burns and Finch 1999). Chemical weathering of these rocks is the likely process that leached out uranium that was later deposited in sandstone-type uranium deposits (see below).

Where uranium is in sufficient concentration in rock to be economically recoverable, it is called an ore body. More detailed information on ore deposit geology can be found in Guilbert and Park (1996) and Edwards and Atkinson (1986). Uranium resources of U.S. economic interest are primarily found in four main types of geologic deposits:

Sandstone Deposits
Sandstones contain approximately 33 percent of uranium resources worldwide, whereas they constitute the main source of uranium (over 95% of reserves and production) in the United States. The principal U.S. sandstone deposits of uranium are in the Colorado Plateau, the Wyoming Basin, the Texas Coastal Plain, and Nebraska. Sandstone uranium deposits in the United States were mostly commonly formed when uranium was introduced after the sediment was deposited, whereas some sandstone uranium deposits in other parts of the world (most notably in Canada and South Africa) are paleoplacers, in which uranium minerals were concentrated as heavy minerals in the sediments as they were deposited.

An important subset of sandstone deposits are breccia pipe deposits found primarily in northern Arizona; collapse structures in bedded sedimentary rocks resulted in the accumulation of uranium in circular deposits mimicking volcanic rock structures. The presence of uranium, copper, silver, vanadium and other valuable metals may occur in breccia pipes—the Orphan Mine (see

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[10] The oxidation state or oxidation number is defined as the sum of negative and positive charges in an atom, which indirectly indicates the number of electrons it has accepted or donated. Hexavalent means that the uranium atom has six more protons than electrons, and thus a net positive charge of +6.

Appendix III) is an example of this type of deposit in which structural geologic features controlled mineral accumulations in sandstones and mudstones.

Vein Deposits

Typically, these deposits occur in or near structures (faults, fractures, shear zones, etc.). Uranium is mineralized in cavities, fissures, cracks, and similar porous openings in veins (as well as breccias and pipes) usually cross-cutting the enclosing rock, and is usually present with accumulations of ore minerals and gangue (non-ore minerals) distinctly different from the surrounding rock. The dimensions of cracks and vesicles (openings or cavities in volcanic rocks) may vary considerably, as can the overall size of the vein ore body. Some ore bodies have been very small (several tons), but rich in uranium. Uraninite and pitchblende are the dominant minerals, with some accessory minerals.

Phosphate Deposits

Sedimentary marine phosphorite is the primary source of uranium in this category. An estimated four million tons of uranium could be extracted from U.S. phosphate deposits. While marketable phosphatic material obtained from phosphate deposits typically contains only 50–200 ppm uranium, the large quantity (approximately 150 million MTs per year) of crude ore rock produced in the United States (Jasinski 2003) makes it a potentially significant source of uranium.

Disseminated Deposits

Typically, these deposits are associated with granites, pegmatites, and syenites. The size, shape, and concentration of the ore bodies vary significantly. Secondary enrichment of the primary mineralization helped to form the ore grade that typically ranges between 0.05 and 0.15 percent. Deposits near Spokane, Washington, and Bokan Mountain in Alaska, are the most prominent disseminated deposits in the United States, though their production was insignificant in comparison to that derived from other types of deposits such as sandstones.

A fifth type of deposit is important to production in Canada:

Unconformity Deposits

This type of deposit is high-grade ore that occurs along and just below major Precambrian unconformities. Ore is often associated with graphite schists.

In defining what is ore, assumptions are made about the concentration in the rock; the cost of mining, processing, refinement, waste management, and site restoration; and the market value of the metal. Material too low in uranium to merit processing and refinement is often called protore, a nominal material that is currently uneconomical. Soil and rock that is otherwise essentially at background uranium and radiation levels, which is removed to gain access to underlying ore, is called overburden.

Most uranium mining in the United States has taken place in the expansive Colorado Plateau region straddling the Four Corners where Utah, Colorado, New Mexico, and Arizona meet. Figure 1.1 illustrates the extent of the Colorado Plateau and the general locations of uranium mines within the Colorado Plateau, although not all mines are shown; for example, numerous watersheds have over 100 mines by themselves. The source of the mine information used for this map is the Minerals Availability System/Mineral Industry Location System database (MAS/MILS) developed by the U.S. Bureau of Mines (McFaul et al. 2000), which has been included as a portion of the EPA Uranium Location Database (U.S. EPA 2006b). These mines have documented production, and represent over 4000 records contained within the larger EPA database, which contains over 14,000 records. Other mine location information in the EPA

database has been collected from several cooperating state, Tribal, and federal agencies. Mine locations in the EPA database, including MAS/MILS sites, were compared to U.S. Geological Survey topographic maps and one another in order to obtain an indication of accuracy and reliability. While the MAS/MILS data has known flaws, and sites shown in Figure 1.1 do not constitute all known uranium mines and fields, it provides a general overview of uranium mine geographic distributions in the western U.S. The larger data sets that comprise the EPA Uranium Location Database are discussed in the database documentation (U.S. EPA 2006b).

Major geologic formations noted for high uranium are the sedimentary Chinle (Triassic) and Morrison (Jurassic) Formations. The Chinle and Morrison are characterized by permeable streambed deposits of highly variable sized and sorted pebbles and sands, with associated concentrated pockets of organic matter from trees, branches, grasses, etc. Later blankets of volcanic ash provided a source of uranium to leach into the permeable rocks of the Chinle and Morrison. The uranium-laden leachate followed the highly permeable stream channel and mudstone formations, and upon reaching the reducing environment caused by high organic matter, precipitated uranium into void spaces, typically as uraninite. The association with organics resulted in some locales where very small—but very high-concentration—uranium deposits have been found, including as petrified logs. Thus, one-man mining operations could target small, rich deposits profitably.

Uranium's Contribution to Natural Background Radiation

Uranium is found in all rock types in varying, but usually small concentrations. Naturally occurring elemental radium and its radioactive decay products can emit radon to the Earth's atmosphere. This section provides a basic discussion on natural background radiation.

Background Gamma Radiation

Numerous studies have examined the occurrence of uranium and its radioactive decay products in U.S. soils. Table 1.3 presents average concentrations of some radionuclides found in igneous and sedimentary rocks that are the principal radionuclides referred to as NORM. There can be more than an order of magnitude difference in radionuclide contents among common igneous rocks. Similarly, deposits known as black shales, found in the eastern U.S. along the Appalachian Mountain front, are not uncommon rocks but are not similar to other U.S. shales as they typically have elevated uranium concentrations.

Figure 1.1. U.S. Geographic Areas Rich in Uranium

Most uranium mining in the United States took place in the expansive Colorado Plateau region straddling the Four Corners where Utah, Colorado, New Mexico, and Arizona meet. This map shows mine locations plotted from McFaul et al. (2000) MAS/MILS database; not all known mine locations are included in that database, so some fields may not be represented. Readers looking for more complete information on state mine locations should refer to U.S. EPA (2006b).

Extent of Colorado Plateau
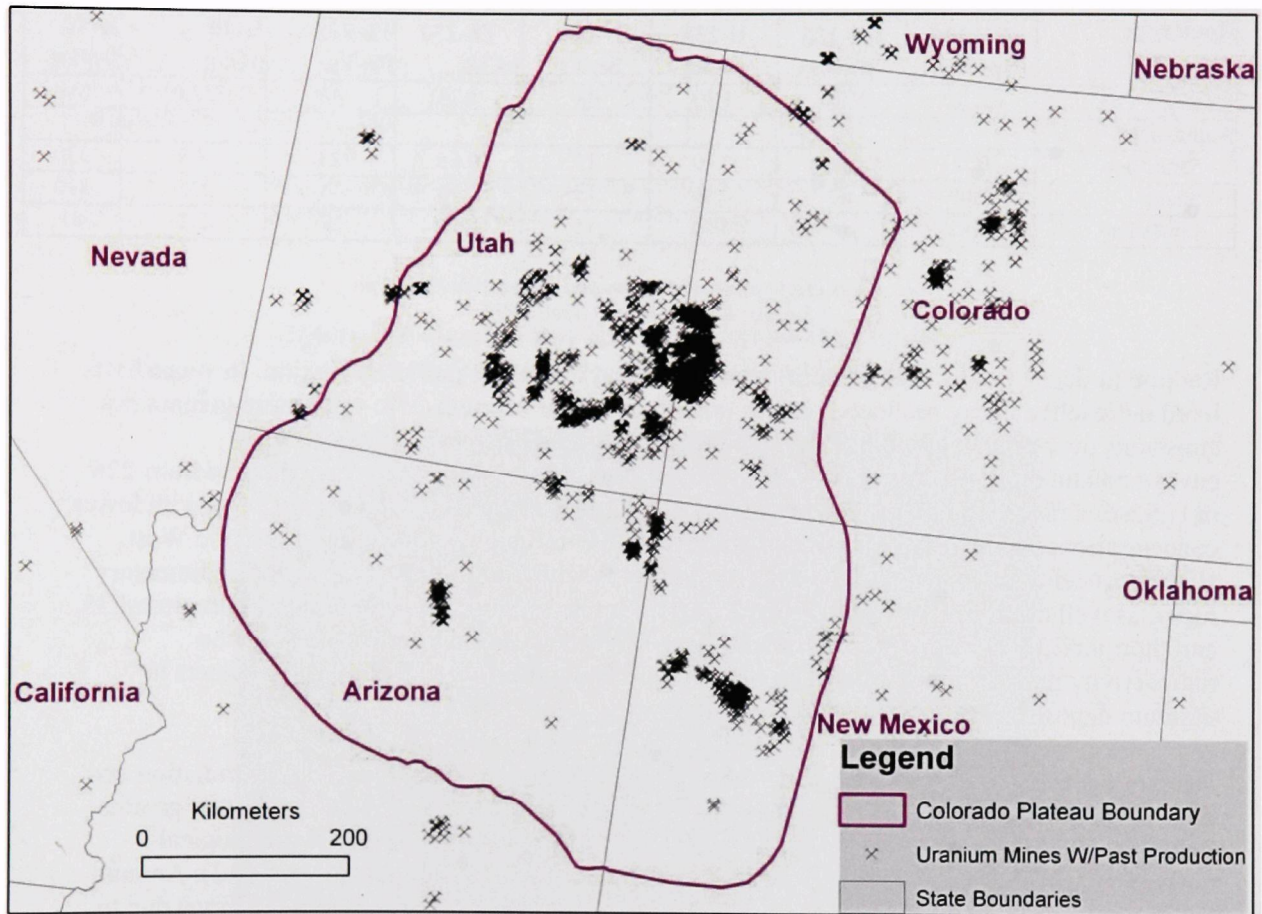
Table 1.3 Concentrations of Certain Natural Radionuclides
in Igneous and Sedimentary Rocks

A concentrating effect can occur as a result of weathering and erosion of igneous rocks. With the exception of uranium-238, concentrations of radionuclides are generally higher in sedimentary rocks. The radionuclides listed are principal NORM radionuclides. The radionuclide contents shown here should be considered average values. Individual rock deposits can have radionuclide contents that may differ significantly from the numbers shown.

Rock type	Radium		Uranium		Thorium		Potassium	
	Ra-226 pCi/g	Ra-226 Bq/kg	U-238 pCi/g	U-238 Bq/kg	Th-232 pCi/g	Th-232 Bq/kg	K-40 pCi/g	K-40 Bq/kg
Igneous	1.30	48	1.30	48	1.30	48	22.0	810
Sedimentary								
Sandstone	0.71	26	0.40	15	0.65	24	8.8	330
Shale	1.08	40	0.40	15	1.10	41	22.0	810
Limestone	0.42	16	0.40	15	0.14	5	2.2	81

Note: Units are in picocuries/gram and Becquerels/kilogram.
Source: Eisenbud and Gesell 1997.

Radium (a decay product of uranium) primarily decays by alpha particle emission. Its own short-lived radioactive decay products, such as polonium-210 or bismuth-214, yield more gamma ray emissions over time, making radium an important contributor to overall human and environmental exposure to radiation, or radiation dose. In general, concentrations of radium-226 in U.S. soils range from 0.4 to 1.3 pCi/g (16 to 48 Bq/kg) (Eisenbud and Gesell 1997), with lower concentrations found in the eastern part of the country, and higher concentrations in the West. Higher concentrations may also be found in locations with uraniferous igneous and sedimentary rocks, as well as phosphatic rock deposits. In addition to radium-226, uranium-238, uranium-235, and thorium-232, there are radioactive decay products that may substantially add to the radioactivity present where these radionuclides are in equilibrium to their decay products in uranium deposits, and mine or mine waste locations

Primary contributors of radiation from the natural environment are soil gamma ray radiation and inhaled radon. A 1987 study (NCRP 1987b), citing a 1972 review by Oakley, estimated gamma radiation doses to the U.S. population from terrestrial sources, based on aerial radiological measuring surveys by the U.S. Atomic Energy Commission (Table 1.4 and Figure 1.2). Annual doses for people living in brick homes may increase up to 10 milliRems/year (mRem/yr) due to naturally occurring thorium, uranium, and radium found in clays often used to make bricks. Additional data on the distribution of radium in the U.S. can be found in Myrick et al. (1981). Two additional studies of the National Council for Radiation Protection (NRCP 1993, 1984) examined the impacts of exposure to uranium and it's radon daughter decay products, and radiation protection in the mineral extraction industry, respectively.

Table 1.4 Absorbed Dose Rate in Air from Terrestrial Radiation Sources
(in milliRems/year, milliSieverts/year and microGrays/year)

Natural geologic accumulations of radionuclides in the Colorado Plateau,
the principal mining area for uranium in the United States,
result in increased exposure rates for humans living in that environment.

region	1960 Population Covered by Surveys	Absorbed Dose Rate in Air (microGy/yr)	Dose in mrem/yr (mSv/yr)
Coastal Plain	6,759,772	230	23 (0.23)
Non-coastal Plain (excluding Denver)	46,781,330	460	46 (0.46)
Colorado Plateau (Denver)	1,073,624	900	90 (0.90)
Population-Weighted Average		**440**	**44 (0.44)**

Note: Results are based on population-weighted aerial radiological survey data.
100 microGy/yr x 0.1 = 0.10 mSv/yr = 10 mRem/yr. Rem = Roentgen equivalent in man.
Sources: NCRP 1987b; Oakley 1972.

Figure 1.2 Gamma Ray Radiation Across the United States
Terrestrial Gamma-Ray Exposure at 1m above ground.
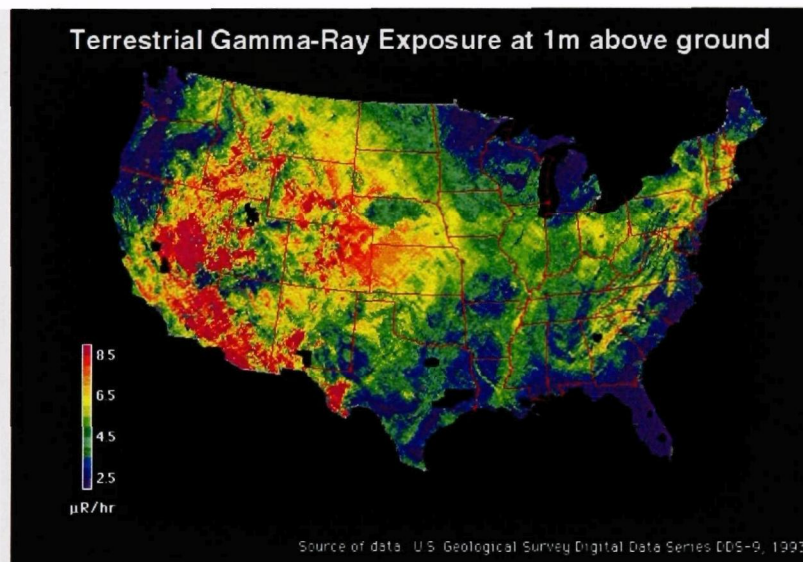
Note: Results are based on national aerial gamma ray surveys.
Colors/shading reflect exposure in µR per hour (micro Roentgens per hour) according to the map.
Source: USGS 1993.

<u>Radon in Homes</u>

The average radiation dose to an individual in the United States from all sources is about 360 mRem/yr (3.6 milliSieverts). Typical values for annual exposure to radiation within the United States are summarized in Table 1.5. Radon occurs in the environment and is listed separately in that table because of radon's significant contribution to radiation exposure: 200 mRem (two mSv) of the estimated average dose from all sources.[11] Most of the radon dose comes from indoor exposure in homes, schools, and other buildings. The radon is generated by rocks and soil underlying the man-made structures; it seeps into the buildings through cracks and pore spaces of the foundations. Some radon is also generated from the building materials used in construction. Figure 1.3 presents short-term screening average U.S. indoor air concentrations of radon by county.[12]

Table 1.5 Average Annual Human Exposure to Radiation

*Natural sources of human exposure to radiation, primarily in the form of radon,
usually outweigh manmade sources, though medical exposures have
become more prominent in recent years.*

Sources of Radiation	Average Exposure in mRem/yr (mSv/yr)	Typical Range of Variability in mRem/yr (mSv/yr)
Natural Sources	**300 (3)**	
Radon	200 (2)	30–800 (0.3-8)
Internal	40 (0.4)	20–100 (0.02-1.0)
Cosmic	30 (0.3)	30–80 (0.3-0.8)
Terrestrial	30 (0.3)	10–80 (0.1-0.8)
Man-made Sources	**61 (0.61)**	
Medical	50 (0.5)	
Consumer products	10 (0.1)	
Other (nuclear fuel cycle and occupational exposure)	1 (0.01)	
Total	**361 (3.6)**	**90–1,060 (0.9-10.6)**

*Sources: NCRP 1987b for average exposure values;
U.S. NRC 1994 for ranges of variability; Fisher 2003 for radon.*

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[11] Cosmic radiation comes from outer space. Some of it penetrates through the atmosphere covering the Earth. The amount of cosmic radiation will vary, depending on the altitude and latitude where one lives. Internal radiation comes primarily from ingested natural radioactive substances, such as potassium-40.

[12] See http://www.epa.gov/radon for more information.

**Figure 1.3 Average Indoor Air Screening-Level Concentrations
of Radon in the United States**
*The highest radon levels are generally reflected in counties located along
the Appalachian Mountains, Rocky Mountains, and north central states.*

EPA Map of Radon Zones
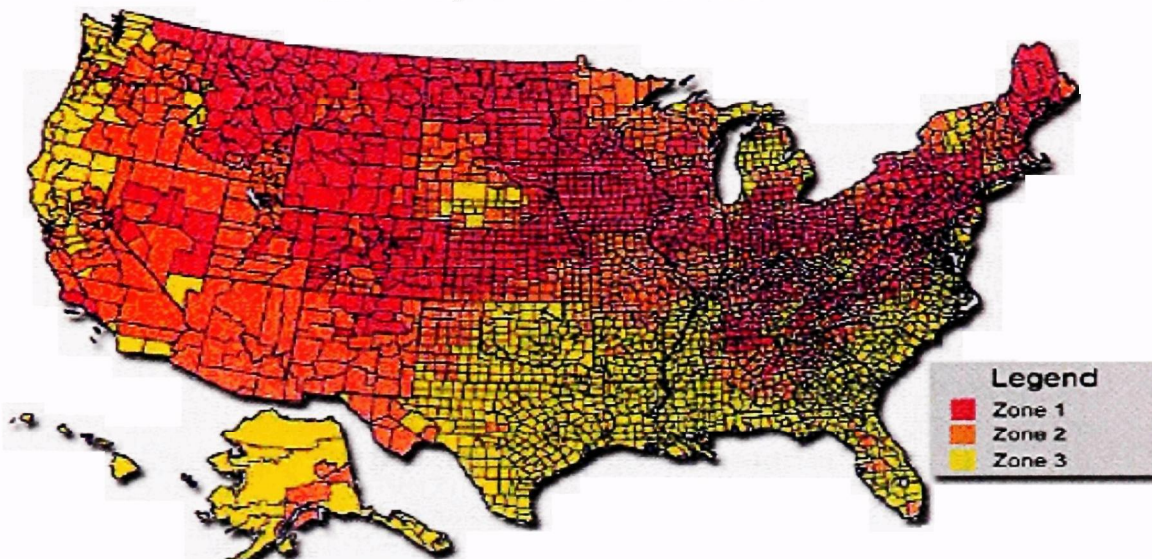
Average Indoor Screening Levels
Zone 1 counties: greater than 4 pCi/L (0.148 Bq/L)
Zone 2 counties: between 2 and 4 pCi/L (0.074 and 0.148 Bq/L)
Zone 3 counties: less than 2 pCi/L (less than 0.074 Bq/L)

*Note: See http://www.epa.gov/iaq/radon/zonemap.html to access an on-line
version of this figure, which allows county-by-county information.
Source: U.S. EPA 1993c*

Uranium in Water

Just as uranium is found in virtually all rock and soil, it is essentially ubiquitous in groundwater. Groundwater concentrations tend to reflect overall bedrock averages and can vary widely. While surface waters, originating primarily from rain and snow melt, are typically very low in uranium and other TENORM radionuclides, to the point where they cannot be measured, groundwater can be relatively high in radionuclides of both primary and anthropogenic origin.

Water is perhaps the most significant means of dispersal of uranium and related TENORM in the environment from mines and mine wastes. Surface waters contaminated by surface erosion of mines and wastes maypercolate into groundwater, and contaminated water travels underground through mines or drill holes into the groundwater. Uranium is very soluble in acidic and alkaline waters and can be transported easily from a mine site. Radium may be leachable as well as carried in particulate form by flowing water (Eisenbud and Gesell 1997). More detail on this topic can be found in Chapter 3. Occurrence of uranium and radium in water has been detailed in case studies on the Orphan Mine, Midnite Mine, Bluewater, and Yazzie-312 Mine (see Appendix III).

EPA has updated its standards for maximum contaminant levels for radionuclides in drinking water (40 CFR 141.66), including a new standard for uranium (65 FR2000a 76708, December 7, 2000), as required by the 1986 amendments to the Safe Drinking Water Act. The standards are:

combined radium 226/228 internal (five pCi/L) (0.185 Bq/L); man-made beta emitters (four mRem annual dose equivalent to the total body or any organ) (0.04 mSv); gross alpha (excluding uranium and radon) standard (15 pCi/L) (0.56 Bq/L); and uranium (30 µg/L). The reader should understand that the uranium standard was based on its identified toxicity to the kidney, and not its potential for causing cancer.

Under the Clean Water Act (See Appendix VI for more detail), mines and mills that discharge must obtain a permit, and must monitor twice a year for specific pollutants determined by the type of ore they mine or process. EPA regulations in 40 CFR 440, Part C, are applicable to discharges from (a) mines either open-pit or underground (ISL operations are excluded), from which uranium, radium and vanadium ores are produced; and (b) mills using the acid leach, alkaline leach, or combined acid and alkaline leach process for the extraction of uranium, radium and vanadium. Only vanadium byproduct from uranium ores is covered under this subpart. With certain exceptions, primarily concerning unusually high storm water events, for existing and new point source dischargers, the maximum concentration for one day of dissolved radium-226 allowed to be discharged is 10 pCi/L with an average 30 day value of three pCi/l, for total radium-226 the amount allowed to be discharged for one day is 30 pCi/L and 10 pCi/L for an average 30 day concentration. For uranium discharges, the maximum allowable discharge for one day is four milligrams/L, while an average of no more than two milligrams/L is allowed to be discharged over a 30 day period. The same numerical standards for radium apply to uranium mills, though there is no uranium discharge standard.

Industrial Processes and Activities

TENORM may be generated during extraction, processing, treatment, and purification of minerals, petroleum products, or other substances obtained from NORM-containing parent materials. TENORM also includes any radioactive materials made more accessible by human activities. Several hundred million metric tons (MTs) of TENORM are generated each year by a wide variety of industrial processes, ranging from uranium and phosphate mining to the treatment of drinking water. Although conventional uranium mining is the central focus of this report and will be discussed in more detail in Chapter 2, the section below briefly discusses activities or processes, other than uranium mining, that produce TENORM as a result of the co-occurrence of uranium and its daughter radionuclides in the source rock, soil, or water. However, not all ores of these commodities contain uranium or radium at concentrations above natural background levels in associated rocks. In some instances, the radioactive wastes from mineral processing other than uranium mines have been used as source rock for uranium extraction under NRC license.

Uranium Associations with Other Metal Mining

Quite typically, beginning in the 1940s, uranium mines would open based on the detection of radioactivity at the site and identification of uraniferous mineralization. While some deposits were mined solely for their uranium content, others produced a variety of other minerals, which co-exist with the uranium minerals (Table 1.6). In some cases, exploitation of uranium minerals was secondary to producing another mineral found in greater abundance, commanding a better market price, or less expensive to produce; nevertheless, their combined economic value contributed to the success of the mining venture.

The presence of radioactive minerals was sometimes unexpected, unknown, or ignored in producing one or more minerals at a mine. Many mine sites operated prior to the 1940s, and even after, have not been recognized for the inherent hazards potentially posed by radioactivity in the discarded waste rock or subeconomic ore piles. The geological emplacement or geothermal phenomena that formed other valuable minerals may have concentrated radioactive minerals as well, or the process of mining, beneficiation, and milling may have resulted in a concentration of the radioactive minerals in the waste. In some instances, the mineral(s) being mined may have radioactive elements included in their molecular structure that impart radioactivity to the ore or even the finished product. The EPA (U.S. EPA 2006b) *Uranium Location Database* provides the location of mines with uranium occurrence including those that may have been mined primarily for other minerals.

Table 1.6 Mineral Commodities with Uranium Associations

Several mineral ores often, though not always, have TENORM-associated wastes resulting from the co-occurrence of uranium and radium.

Aluminum (bauxite)	Potassium (potash)
Coal (and coal ash)	Precious metals (gold, silver)
Copper	Rare earths: yttrium, lanthanum, monazite, bastanite, etc.
Fluorospar (fluorite)	Tin
Gypsum	Titanium (leucoxene, ilmenite, rutile)
Molybdenum	Tungsten
Niobium	Vanadium
Phosphate (phosphorus)	Zircon

Source: U.S. EPA 2003b.

Copper Mining

Copper mines have long known to be associated with uranium occurrences internationally, as well as in the U.S. The Bingham Canyon copper mine in Utah produced 150,000 pounds of uranium per year from 1978-1985 and 10,000 pounds per month from February 1987 through the end of 1989 (Chenoweth 1991). The Orphan Mine in Arizona (see Appendix III) was originally claimed for its copper mineralization, but only began production in the 1950s as a result of its rich uranium occurrence. Other mines in the southwest, such as the Yerington Mine in Nevada and Anaconda Mine in Utah have also been reported to have uranium mineralization or production. Uranium recovery from copper leaching is described in McGinley (1980). EPA's report (U.S. EPA 1999) on copper mining in Arizona provides extensive information on TENORM radiation associated with copper mine wastes and groundwater impacts, both from conventional and ISL extraction facilities in that state. Some of the mines listed also were licensed by the Atomic Energy Commission (precursor to the NRC) to produce uranium in addition to copper.

Phosphate Production

Uranium is known to associate with phosphatic deposits primarily because hexavalent uranium complexes well with dissolved phosphate. Phosphate rock contains phosphorite, a form of the mineral apatite, which is known to accommodate uranium. Phosphate rock is the sixth largest mining industry in the United States in terms of volume of material mined. It is mined for the production of phosphoric acid, the great majority of which is used in agricultural fertilizer. About 80 percent of U.S. phosphate mining occurs in south central Florida, though some mining also has occurred in North Carolina, Utah, Idaho, Wyoming, Tennessee, and a few other states (U.S. EPA 1989b; Jasinski 2003).

The phosphate fertilizer industry is a major generator of TENORM. Uranium concentrations in phosphate rock range from 14 to 200 pCi/g (20 to 300 ppm, or about 0.5 Bq/g to 7 Bq/g), and radium concentrations are 18 to 84 pCi/g (about 0.7 to 3 Bq/g) (DeVoto and Stevens 1979). In the United States alone, some 150 million MTs of phosphate ore are produced each year, which contain radioactive thorium and its decay progeny, in addition to uranium TENORM. Mineral processing sometimes exposes workers to measurable doses of radioactivity.

Phosphate ore is crushed and digested in sulfuric acid to produce orthophosphoric acid and phosphogypsum. Phosphogypsum is a complex mixture of gypsum ($CaSO_4 \cdot 2H_2O$), silica, and anhydrite ($CaSO_4$). In the process, various other wastes are also formed. Between 80 and 100 percent of the radium in phosphate rock is transported to the phosphogypsum, while about 70 percent of the uranium (and thorium) remains in the phosphoric acid (however, the fractionation of uranium and thorium is variable and still not well characterized) (Guimond 1975; Hull and Burnett 1996; FIPR 1995).

Though uranium concentrations in phosphate ore are low compared to typical uranium ores, the low cost of uranium recovery from secondary phosphate products sometimes makes it profitable to extract uranium as a by-product of phosphate production. Phosphate rock and tailings containing up to 120 ppm of uranium have been mined as a source of uranium (DeVoto and Stevens 1979).

Before EPA required placement of phosphogypsum in environmentally isolated waste piles, called "stacks", to control radon emissions (40 CFR 61, Subpart R), phosphogypsum and waste rock containing uranium and thorium were often used to refill and reclaim open mine pits. Due to pressures to find available land for home building, several of these reclaimed mine pits were subsequently sold as home sites. In 1975, EPA reported that more than 1,000 houses were built over these sites in one Florida county alone. While it has not been determined if this housing may pose a radiation hazard to the occupants, during its study EPA found some elevated levels of radiation and radon (U.S. EPA 1975).

Elemental phosphorus is produced by the thermal process. It is a raw material used primarily in chemical and food production, primarily from ore deposits in Idaho. This process also produces TENORM wastes, such as slags, containing radium and uranium.

Coal Combustion
Most coal contains uranium and its progeny radionuclides at levels about the same as, or less than other rocks of the Earth's crust (UNSCEAR 1982). Uranium TENORM emerges from coal-burning plant furnaces predominantly in fly ash, which is fused and chemically stable. Coal fly ash is derived from inorganic materials that were co-deposited with the organic detritus that produced the coal beds. Uranium in coal may be a combination of detrital mineral matter and uranium deposited later through adsorption by, or oxidation of, organic matter in the lignite or coal. In one instance in the 1960s, certain lignitic coals from North Dakota were mined and burned in order to further concentrate the high levels of uranium already present in the coal; the resulting ash was then taken to a uranium mill in Colorado to process into uranium yellowcake[13]

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[13] See http://www.eia.doe.gov/cneaf/nuclear/page/umtra/belfield_title1.html for more information.

Principal nonradioactive ash constituents are the metal oxides of silica and alumina, often comprising 80–90 percent, with smaller percentages of other metal oxides, including iron, calcium, sodium, tin, magnesium, and potassium. Pollution control devices in modern power plants usually capture about 99 percent of fly ash, and devices in some older plants capture about 90 percent. However, those devices do not capture radon gas. In addition to ash, power plants produce slag, sludge, and other waste products that may contain uranium TENORM.

The amount of ash generated is proportional to the amount of coal consumed and the coal ash content. The ash content of coal will vary according to the depositional environment. The average ash content of coal burned by the U.S. electric utility industry is approximately 10 percent, meaning that uranium in coal is concentrated roughly 10 times in the ash. For coal with a 10 percent ash content, a 1,000 megawatt plant may produce over 1,500 tons of ash during a 24-hour period. However, the actual quantity of ash produced also depends on the plant's design and efficiency and the coal's energy content.

Though the concentrations are low, the total amount of TENORM in fly ash is noteworthy (Beck et al. 1980; Beck 1989). For example, in 2004, U.S. electric power plants burned approximately 921 million MTs of coal (U.S. DOE/EIA 2005d). If that amount of coal is burned with 1.5 ppm uranium, 1,381 MTs of uranium would be concentrated, in addition to other TENORM quantities.

Other coals are quoted as ranging from up to 25 ppm of uranium and 80 ppm of thorium. Based on analyses of nearly 7,000 samples, of all coal provinces and coal ranks, an EPA study found that the range of uranium in U.S. coal was 0.010–75 ppm (U.S. EPA 1995b).

Most fly ash is buried, but increasingly fly ash is being used for commercial applications. A significant quantity of fly ash (Class C) is considered cementitious (having the properties of cement, the principal binding agent in concrete) which makes it a very useful material. The relatively uniform small particle size, surface reactivity, and bulk chemical composition—particularly if alkali elements are abundant—lend properties to coal ash, slag, and flue gas waste material that have numerous useful commercial applications. These include: flowable fill, structural fill, road base/subbase, coal mining applications, mineral filler in asphalt, snow and ice road control, blasting grit and roofing granules, grouting, waste solidification and stabilization, and wall board (ACAA 1995, 1996; U.S. DOE/EIA 1993; EPRI 1988).

Heavy Mineral Sands
Many of the minerals which make up this commodity contain significant percentages of uranium and thorium. As a result of their inherent hardness, weight (specific gravity), and other physical properties, certain minerals are naturally resistant to erosion and to physical and chemical breakdown over geologic time. Accumulations of these minerals results in sedimentary sand deposits commonly called "heavy mineral sands," or sometimes "black sands," because they are dominated by black minerals. These deposits, if they occur in easily accessible locations and in sufficient size, may be mined to concentrate and extract valuable industrial metals (U.S. EPA 1990).

Typical minerals that may be found in these deposits include garnet; titanium-rich rutile, ilmenite, and leucoxene; thorium-rich monazite; and uranium-rich zircon. All of these minerals, and several others typically occurring in the deposits, are radioactive due to: the presence of uranium, thorium, and radium in their molecular matrix; radioactive coatings washed into the deposits from elsewhere; or the chemical and physical weathering of radioactive mineral grains in the sand deposit. The wastes from extracting these minerals, and often the finished products resulting from mineral processing, may retain some or all of their natural radioactivity (CRCPD 1994).

Although monazite is mined incidentally along with other minerals in heavy mineral sand deposits, it is not currently being used commercially in the United States, and is usually returned to the extraction site as a waste. The uranium oxide content of monazite sands in the Southeast was measured at 0.47 percent (Mertie 1953). Monazite from the Green Cove Springs deposit in Florida, which produced monazite prior to 1995, averaged 4.44 percent thorium oxide (Staatz et al. 1980).

The major U.S. mining operations for titanium sands have been located in Stoney Creek, Virginia, and Simi Valley, California, and along the Trail Ridge formation, an ancient sand dune deposit that extends from northeastern Florida to southeastern Georgia. However, most titanium ore (separated sands mostly, rather than finished titanium dioxide powder) is imported. Although as a metal, titanium is well known for its corrosion resistance and for its high strength-to-weight ratio, approximately 95 percent of titanium is consumed in the form of titanium dioxide pigment in paints, paper, and plastics. Other end uses of titanium include ceramics, chemicals, welding rod coatings, heavy aggregate, and steel furnace flux (USGS 1973). There has been no study on disposal of any residual radioactive wastes from these industries in the U.S.

Zirconium is a silvery-white metal obtained from zircon sands (Brady et al. 1997), while hafnium is a ductile metal, with a brilliant silver luster. Most zirconium minerals contain 1-5 percent hafnium (CRC 1994). Zircon production is usually a byproduct of mining and extracting titanium minerals from ilmenite and rutile ores. Zircon has been produced from dredging operations in Florida, and now Virginia. Major end-use categories for zircon include abrasives, ceramics, refractories, and foundry applications. Zircon is consumed directly for abrasives and welding and as welding flux. Zircon sands and finely ground zircon (termed zircon "flour") are consumed in foundry molds, refractories, and ceramics. Residual radioactive wastes from these industries have been reported to be disposed in industrial landfills, and there have been instances where abandoned barrels of zircon flour, and sites contaminated with zircon wastes have been the subject of Superfund cleanup and removal actions. Table 1.7 presents radioactivity concentrations reported by the CRCPD for zircon and titanium process ore and wastes

Table 1.7 Radionuclide Concentrations in Process and Waste Samples
Radium concentrations can be highly variable for titanium and zircon ores and wastes, and dependent on ore source.

Process Ores	^{226}Radium Concentrations in pCi/g (Bq/Kg)
Titanium	
Rutile	15 (555)
Leucoxene	12 (444)
Dry ponds (~5 cm depth)	45 (1665)
Dry ponds (surface)	20 (740)
Settling pond solids	17 (0.73)
Sludge pile	4-25 (148-925)
Zircon	
Chlorinator residues No. 1	150-1,300 (5550-48100)
Chlorinator residues No. 2	230-890 (8510-32930)
Clarifier sludge	87-150 (3219-5550)

Source: CRCPD 1994.

Chapter 2. Uranium Mining and Extraction Processes in the United States

In 1946, Congress passed the Atomic Energy Act (AEA), establishing the Atomic Energy Commission (AEC) and designating it as the sole purchasing agent for domestically produced uranium. The AEA also set fixed prices for uranium ore and provided production incentives (e.g., including access roads, haulage allowances, and buying stations) in an effort to bolster development within the domestic uranium industry. Since then, the industry has gone through two boom-to-bust cycles (U.S. DOE/EIA 1992). The first of these cycles, in the 1950s, was prompted by the demand generated by the U.S. government's weapons program. The second, in the 1970s to early 1980s, was fueled by expectations for increasing demand from commercial nuclear power production and the "energy crisis". Since the 1970s, the NRC succeeded the AEC in the role of licensing uranium extraction operations, but the demand and price of uranium has been determined by external market forces. Rising demand, beginning in 2003 for uranium has begun to increase production in the domestic industry. The importance of the uranium market and price of uranium is their role in mining industry decisions. Some of these decisions are: how to extract ore from a mineral deposit, how many and which mineral deposits should be mined, and when they should be mined. Those decisions ultimately affect the volumes of waste produced and how it is managed.

This chapter examines the location and geology of uranium deposits in the United States, the methods used to mine uranium, and the methods used to extract it from ore. Many of the geological and mining terms used in the text that follows are defined in the chapter and are also in included in the glossary in Appendix I.

The Early Years of Uranium Production

As a result of the AEC's financial incentives—first announced in 1948 and 1949 and then increased in 1951—uranium prospectors searched prospective areas of the United States throughout the 1950s for radioactivity that might signal a viable uranium deposit. Prospectors locating areas with mining potential would file claims for the discovery site and nearby areas. The ownership claims were regulated according to the Mining Law of 1872 and were enforced by the U.S. Department of Interior. To maintain ownership of these claims, prospectors needed to perform a variety of activities every year, including digging small pits, adits[1], and trenches. If they found ore grade material higher than 0.10 percent uranium, they would mine the material and ship it to regional AEC buying stations for sale. AEC offered bonuses for shipments meeting minimum criteria.

In many parts of the Colorado Plateau, the characteristic geologic forms of uranium ore bodies were small to moderate-sized isolated pods or linear sinuous channels of ore, as opposed to large lithologic[2] beds typical of coal or iron. As a result, thousands of diminutive mines were developed in the Plateau region on ore bodies sometimes as small as a single uraniferous petrified log weighing a few metric tons. In many cases, these ore bodies were clustered into districts (Table 2.1.), and ores were shipped from producing properties to centralized mills. These small mines produced small quantities of waste rock typically discarded within several to over 100 yards (several to about 100 meters) of the mine opening or pit. Mine maps typically show extensive underground mining following ore zones with only small piles of

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[1] Adits are horizontal or nearly horizontal passages driven from the surface for the working or dewatering of a mine. If driven through a hill or mountain to the surface on the other side it would be a tunnel.

[2] Lithologic is defined as character of a rock described in terms of its structure, color, mineral composition, grain size, and arrangement of its component parts; all those visible features that in the aggregate impart individuality to the rock. Lithology is the basis of correlation in coal and other types of mines and commonly is reliable over a distance of a few to several miles.

waste rock at the mouth of the mine entry. Mines of this type, now abandoned, are scattered over wide areas of southeastern Utah, southwestern Colorado, northwestern New Mexico, and northeastern Arizona, as can be seen in Figure 2.1. As described further in Chapter 3 of this report, the mines which were abandoned or left unrestored prior to the early 1970s left residual wastes that are a main focus of this study. The migration of radionuclides and other hazardous substances from those mines and their waste piles have resulted from biologic, hydrologic, wind, and human actions, and are discussed in more detail in Chapter 3 and Volume II of this report (U.S. EPA 2006a).

The primary database for uranium mine locations for the public has been the MAS/MILS (McFaul et al. 2000) database. However, the MAS/MILS data used to construct Figure 2.1 has known flaws, and sites shown on the map using the database do not constitute all known uranium mines and fields. For example, the Crow Butte *in situ* leach (ISL) field in Northwest Nebraska near the Wyoming border is not included; however Figure 2.9, based on different data compiled in the EPA Uranium Location Database (U.S. EPA 2006b), does show the location of the Northwest Nebraska uranium district. The MAS/MILS database though, does provide a general overview of uranium mine geographic distributions in the western U.S. The larger data sets that comprise the EPA Uranium Location Database are discussed in the database documentation (U.S. EPA 2006b).

Table 2.1. Major U.S. Uranium Mining Districts

Several major uranium districts produced uranium ore in the past and contain potential for future exploitation.

Uranium District	State
Spokane	Washington
Wind River Central Wyoming	Wyoming
Washakie Sand Wash	Wyoming, Colorado
Powder River	Wyoming, Montana
Northwest Nebraska	Nebraska
Uravan Front Range Marshall Pass Tallahassee Creek	Paradox Basin, Colorado & Utah
Paradox Basin	Colorado, Utah
Marysvale	Utah
Northern Arizona	Arizona
Grants Mineral Belt	New Mexico, Arizona
Texas Gulf Coast	Texas

Source: U.S. DOE/EIA 1997.

Figure 2.1. Mines and Other Locations with Uranium in the Western U.S.

*Thousands of uranium mine sites are scattered over wide areas of the western United States.
This map shows locations provided in the MAS/MILS database.*
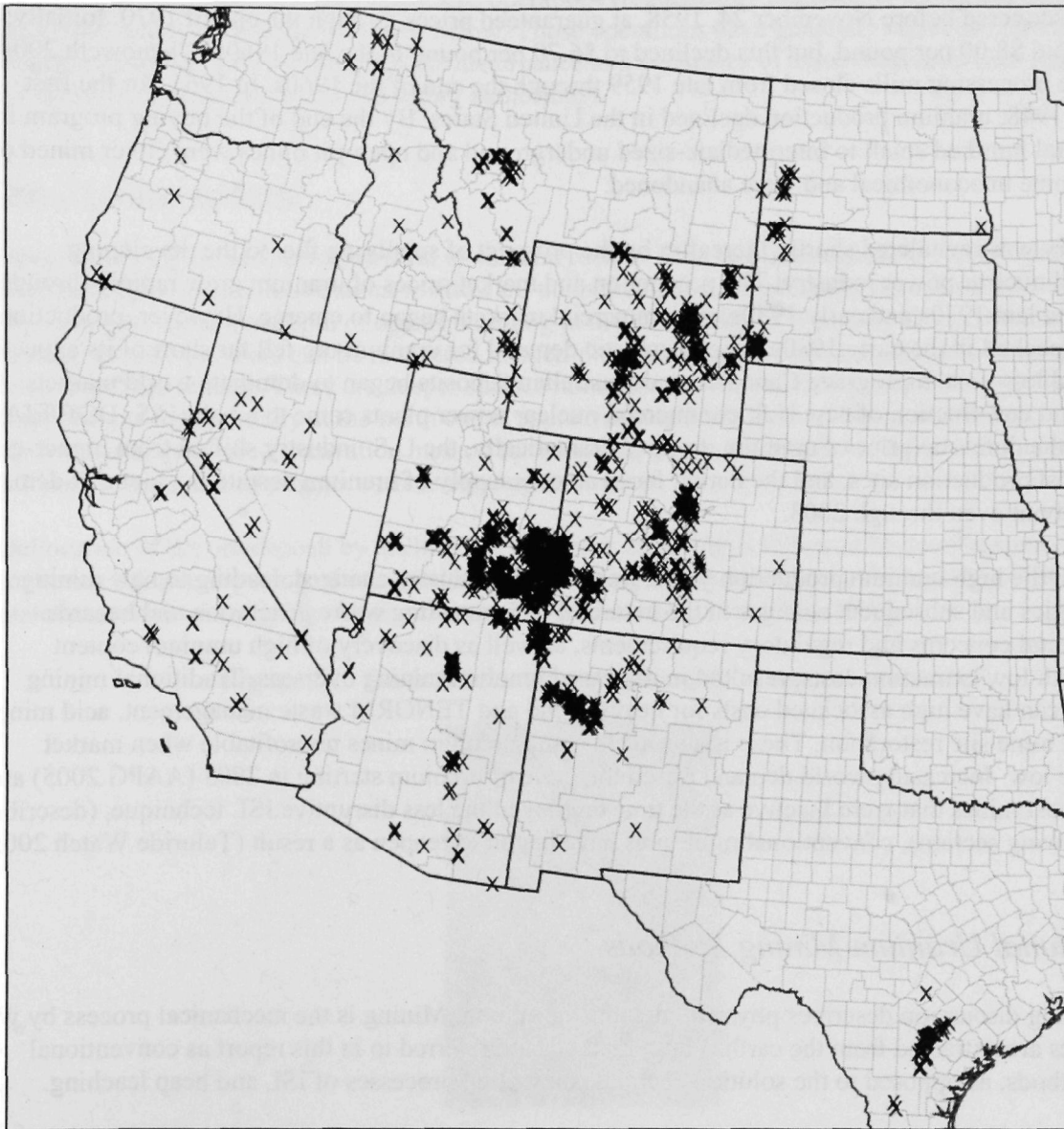
Legend

x   MAS/MILS Uranium Mines

Source of Mine Information:
EPA Uranium Location Database

Km
500

N

Source: (U.S. EPA 2006b)

Large companies were also in the uranium prospecting business. Many mining properties proved to have much larger ore bodies than originally thought, both on the Colorado Plateau and in other states. Extensive mining operations were developed at these sites. Since the early 1960s, most uranium has been mined on a larger scale than early mining efforts and conventional mining techniques were established to recover the ores.

Although the AEC incentives ceased in 1962, the agency continued to purchase ore from properties with reserves discovered before November 24, 1958, at guaranteed prices through the end of 1970. Initially, the AEC paid $8.00 per pound, but this declined to $6.70 per pound in the late 1960s (Chenoweth 2004). Several ore processing mills closed from late 1959 through the end of the 1960s. In 1961, for the first time since 1948, uranium production declined in the United States. By the end of the buying program in 1970, several hundred small to intermediate-sized underground and open-pit mines were either mined out or had become uneconomical and were abandoned.

The industry was revitalized shortly thereafter by the prospect of supplying fuel to the developing commercial nuclear power industry. The production and market prices of uranium grew rapidly through the mid- and late 1970s and early 1980s, as commercial markets began to emerge. However, production and prices peaked in the early 1980s, when domestic demand for uranium ore fell far short of its expected growth, and low-cost, high-grade Canadian and Australian deposits began to dominate world markets. As planning and construction of new U.S. commercial nuclear power plants came to a halt (U.S. DOE/EIA 1992) and the domestic price of uranium dropped dramatically, the U.S. industry shifted from higher-cost to lower-cost production sites, and the nation faced an oversupply of uranium despite the fact that demand remained about even through 2003.

Throughout the high uranium production years, trends in the industry changed, leading to new mining methodologies and subsequent changes in the nature of their resulting waste generation and hazards. Environmental concerns and regulatory requirements, as well as discovery of high uranium content deposits with low extraction costs, resulted in increased uranium mining overseas. Traditional mining techniques can have high associated costs for heavy metal and TENORM waste management, acid mine runoff, and mine site restoration. These issues made many uranium mines unprofitable when market prices were low. Increasing world demand raised the price of uranium starting in 2003 (AAPG 2005) and although most mines that were inactive at the time employed the less disruptive ISL technique, (described in the following section), conventional mine sites have begun to reopen as a result (Teluride Watch 2005).

Conventional Uranium Mining Methods

The following discussion describes physical methods of mining. Mining is the mechanical process by which mineral ores are extracted from the earth. These methods are referred to in this report as conventional mining methods, as opposed to the solution chemical extraction processes of ISL and heap leaching.

Ore is a mineral source from which a valuable commodity (e.g., metal) is recovered. The term ore implies economic viability, given the concentration of metal in the host rock, the costs of extraction, processing and refinement, waste management, site restoration, and the market value of the metal. Protore is conventionally 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. Waste materials that are, or could be classified as, technologically enhanced, include overburden, unreclaimed protore, waste rock, drill and core cuttings, liquid wastes and pit water (for more detailed discussion, see Chapter 3). The size, grade, depth, and geology of an ore body (or deposit) are used in combination to determine which extraction method is most efficient and economical. Conventional

mining generally refers to open-pit and underground mining. 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 or where the size, shape, and orientation of the ore body may permit more cost-effective underground mining. Since the early 1960s, most uranium has been mined on a larger scale than earlier mining efforts, and, until recently, by using conventional mining techniques. Radioactive mine wastes from conventional open-pit and underground mines are considered to be TENORM, whose regulatory responsibility resides with EPA or the states. In recent years, ISL operations (regulated by the NRC or its Agreement States) in the United States are described further below. Those operations have generally replaced conventional mining because of their minimal surface disturbance and avoidance of associated costs (See Appendix VI for discussion on statutory and regulatory authorities).

Open-Pit (Surface) Mining

Open-pit mining is the surface removal of soil and rock overburden and extraction of ore. Open-pit mines are broad, open excavations that narrow toward the bottom, and are generally used for shallow ore deposits. The maximum depth of open-pit mining in the United States is usually about 550 feet (168 meters). Lower-grade ore can be recovered in open-pit mining, since costs are generally lower compared to underground mining. There are deeper surface mines for copper and other minerals (Berkeley pit in Butte, Montana, reportedly at the north end is approximately 1780 feet, or 543 meters deep). Figure 2.2 shows a commonly used excavation method for removing overburden from surface mines, whereas Figure 2.3 shows the layout of a larger surface mine operation.

Delineation of the ore deposit by drilling and computer modeling is followed by development of a plan for removing and disposing of overburden. This planning is important, since the handling of waste material comprises one of the largest shares of overall mining costs (Grey 1993).

Figure 2.2. Surface Mine Showing Drag Line and Overburden

Source: U.S. EPA 1997

In open-pit mining, topsoil is the natural soil overlying the pit outline, while overburden includes material lying between the topsoil and the uranium ore deposit. In more recent open-pit operations, soil is removed and stockpiled for later site reclamation (i.e., restoration). Overburden is removed using scrapers, mechanical shovels, trucks, and loaders. In some cases, the overburden may be ripped or blasted free for removal. Overburden forms the largest volume of waste, is generally lowest in naturally radioactive elements, and is not as enriched in uranium as protore. Protore is often stockpiled at the mine site as well,

and is much higher in radionuclide or heavy metal content than overburden or soil.

Once the ore body is exposed, radiometric probing is used to define the exact extent of the ore body. Ore, protore, and low-grade mineralized rock are outlined, and plans are developed for mining and stockpiling them. Many times parts of an ore body delineated by drilling cannot be economically mined by open-pit methods. Where parts of the deposit lie adjacent to the bottom of the planned pit, underground mines may be developed from the pit bottom to recover these ores. Often waste material, including overburden, is returned to mined-out areas during mining to reduce hauling costs.

Figure 2.3. Surface Mine
This figure shows a surface mine operation in Nevada.
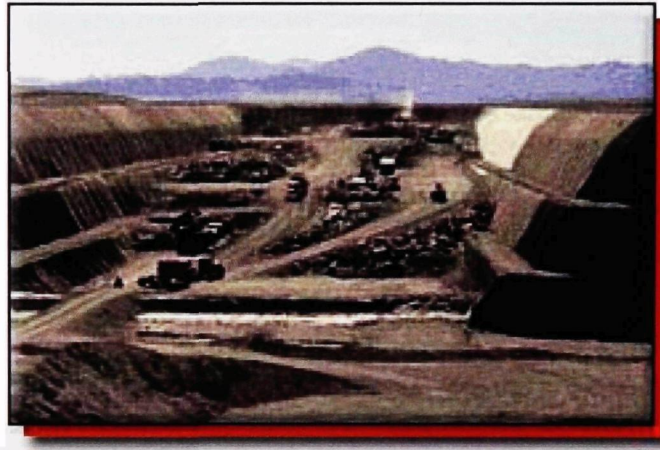
Source: U.S. EPA RCRA Program

"Rim stripping" was a technique applied in areas of the Colorado Plateau. In this type of open-pit mining, the ore body occurred at or near the surface along the edge (or rim) of a canyon. Miners would strip the shallow overburden from the deposit and generally drop the waste material down the adjacent canyon wall. In practice, this mining resembles strip mining for coal in the eastern United States. Rim stripping was generally limited to the edge of the canyon because the overburden grew thicker farther away from the rim.

Underground Mining

Deeper uranium ore deposits require underground mining by one of several excavation techniques, including:

- longwall retreat (a method of underground mining in which the ore bearing rock is removed in one operation by means of a long working face or wall; the space from which the ore has been removed either is allowed to collapse, or is completely or partially filled with stone and debris);
- room and pillar (a conventional method of mining in which natural pillars are left unmined for support between the mined rooms); and,
- panels (a method of mining whereby the workings of a mine are divided into sections, each surrounded by solid strata with only necessary roads through the rock barrier).

The mining method of choice depends on several factors, including the size, shape, depth, and grade of the ore body, the stability of the ground, and economics (Grey 1993). For small ore bodies near the surface, miners may use:

- adits;
- inclines (a slanting shaft from the surface into the underground mine); or,
- small shafts to reach and remove ore.

Larger, deeper deposits may require one or more vertical concrete-lined shafts or declines large enough for motorized vehicles to reach the ore. Stopes (an underground excavation from which ore has been removed in a series of steps) reaching out from the main shaft provide access to the ore.

Ore and waste rock generated during mining are usually removed through shafts via elevators, or carried to the surface in trucks along declines. Because of the high costs of removing such materials, some waste rock may be used underground as backfill material in mined-out areas. As with surface mining, radioactive waste rock in underground mining is generally considered to be TENORM. The extracted ore is stockpiled at the surface or trucked directly to a processing mill, which may be on site or at some centralized location. Figure 2.4 is a diagram of an underground uranium mine with room and pillar excavation.

Figure 2.4. Diagram of Room and Pillar Underground Mining

This figure shows a simplified diagram of a room and pillar underground mining operation. Main vertical shafts connect with underground "rooms" that have been excavated using unmined rock columns as support pillars. Rail cars move ore and waste through the mine.
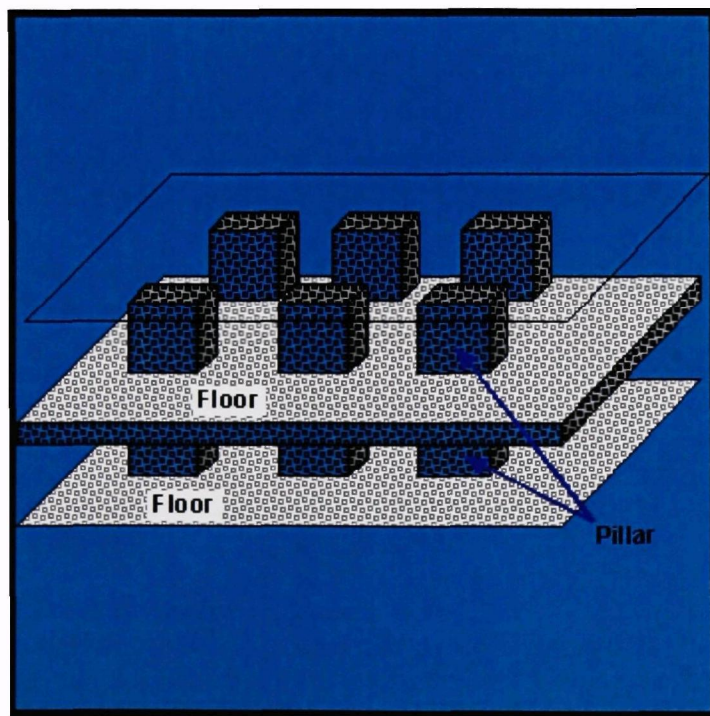
Source: U.S. EPA (1997)

Unconventional Mining Methods

Open-pit and underground mining methods, both of which rely on physical extraction to obtain raw uranium ore, are commonly referred to as conventional mining methods. The reliance on chemical or other means to extract uranium are referred to as unconventional mining methods, even though they may have been used as extraction processes for decades. The sections which follow describe the heap leaching and ISL extraction processes.

Heap Leaching

As this is an extraction process, heap leaching is regulated by the NRC or its Agreement States; the waste rock is considered byproduct material (see Appendix VI). Ore that is removed from open-pit and underground mining operations undergoes further processing to remove and concentrate the uranium; the heap leaching may be located near the mine site. Ore is crushed in a large mill, grounded to sand consistency, and mounded above grade on a prepared pad, usually constructed of clay, coated concrete, or asphalt. A sprinkler system, positioned over the top, continually sprays leach solution over the mound. For ores with low lime content (less than 12 percent), an acid solution is used, while alkaline solutions are used when the lime content is above 12 percent. The leach solution trickles through the ore and mobilizes uranium, as well as other metals, into solution. The solution is collected at the base of the mound by a manifold and processed to extract the uranium. Figure 2.5 below provides an illustration of the process. Heap leaching was used mostly on an experimental basis in the 1970s and 1980s, but is generally not in use in the U.S. today.

Figure 2.5. Illustration of Heap Leaching Process
In this illustration, leaching solutions (either acidic or alkaline) comprising the lixiviant are sprinkled on crushed ore mounded on a liner or leaching pad. Uranium bearing fluids collect by gravity on the bottom of the pile and drain into a pit (or pregnant pond); the fluids are then piped or transported to a mill for further extraction and turned into yellowcake.
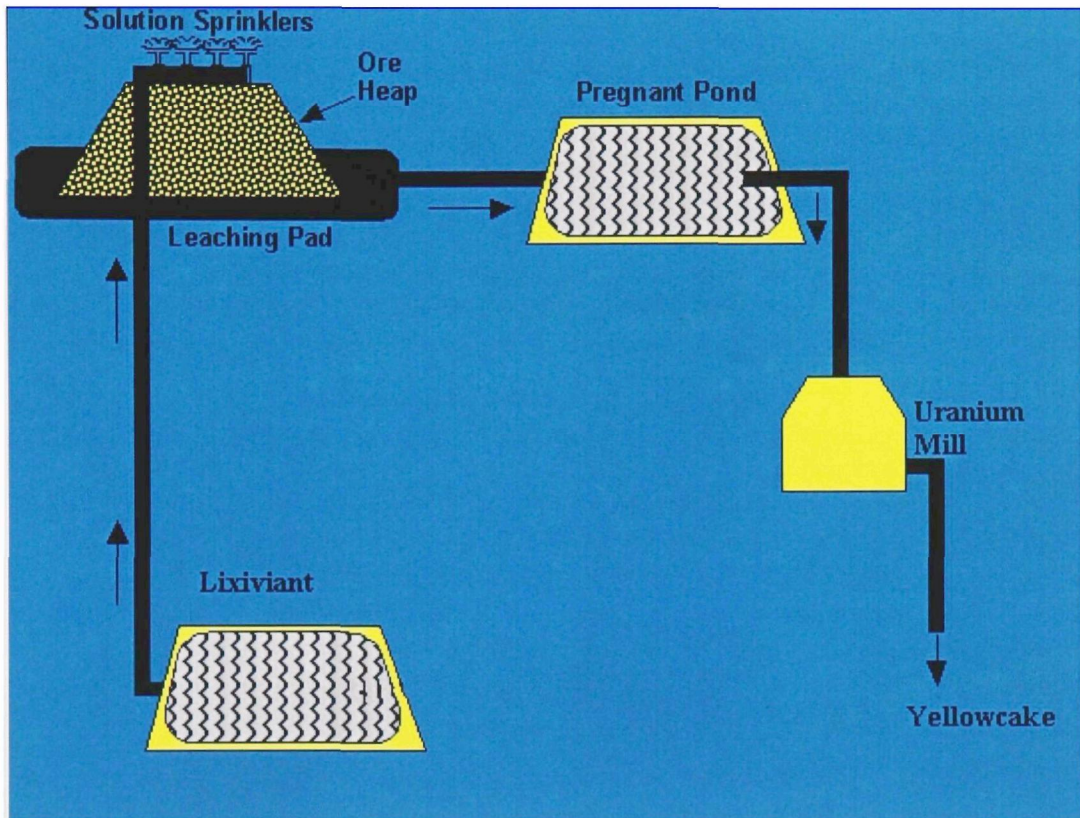
Source: EPA

In Situ Leaching (Solution Mining)

Since this is also an extraction process, ISL is regulated by the NRC or its Agreement States; the waste materials and fluids are considered byproduct material (see Appendix VI). However, EPA standards and requirements for uranium extraction facilities developed under UMTRCA, as well as requirements of EPA's Underground Injection Control (UIC) program are applicable to ISL facilities (See Appendix VI for more information). ISL operations are discussed here to provide a more complete representation of the impacts from uranium production.

ISL is used when specific conditions exist, for example:
- The ore is too deep to be mined economically by conventional means;
- The uranium is present in multiple-layered roll fronts that may be offset by faulting;
- The ore body is below the water table;
- Considerable methane and hydrogen sulfide are associated with the ore;
- The ore grade is low, and the ore body is too thin to mine by conventional means;
- A highly permeable rock formation exists in which uranium can be economically produced.

In this method of extraction, uranium ores are leached underground by the introduction of a solvent solution, called a lixiviant, through injection wells drilled into the ore body. The process does not require the physical extraction of ore from the ground. Lixiviants for uranium mining commonly consist of water containing added oxygen and carbon dioxide or sodium bicarbonate, which mobilize uranium. The lixiviant is injected, passes through the ore body, and mobilizes the uranium. The uranium-bearing solution is pumped to the surface from production wells.

The pregnant leach solution is processed to extract the uranium, usually by ion exchange or by solvent extraction. The ion exchange process employs a resin that, once fully saturated with uranium, is flushed with a highly concentrated salt (e.g., sodium chloride) solution. This reverses the exchange process and releases uranium into the solution. The uranium solution is then sent to another process for concentration, precipitation and drying, as yellowcake. The solvent extraction process relies on unmixable properties between the pregnant leach solution and (uranium) solute. Normally, the solvents are organic compounds that can combine with either cationic or anionic solutes. For example, anionic solutions include amine chains and ammonium compounds, and cationic solutions are phosphoric acid-based. Figure 2.6 shows a simplified version of the ISL process.

Figure 2.6. Illustration of ISL Process

This figure shows a simplified version of how ISL solution mining works. Lixiviant is injected into the ground through a well on the left and far right, the fluid flows underground dissolving uranium and carrying it in solution until it reaches a production well in the center. The fluid carrying dissolved uranium is returned to the surface from the production well, then is piped off to a production facility for refinement into yellowcake.
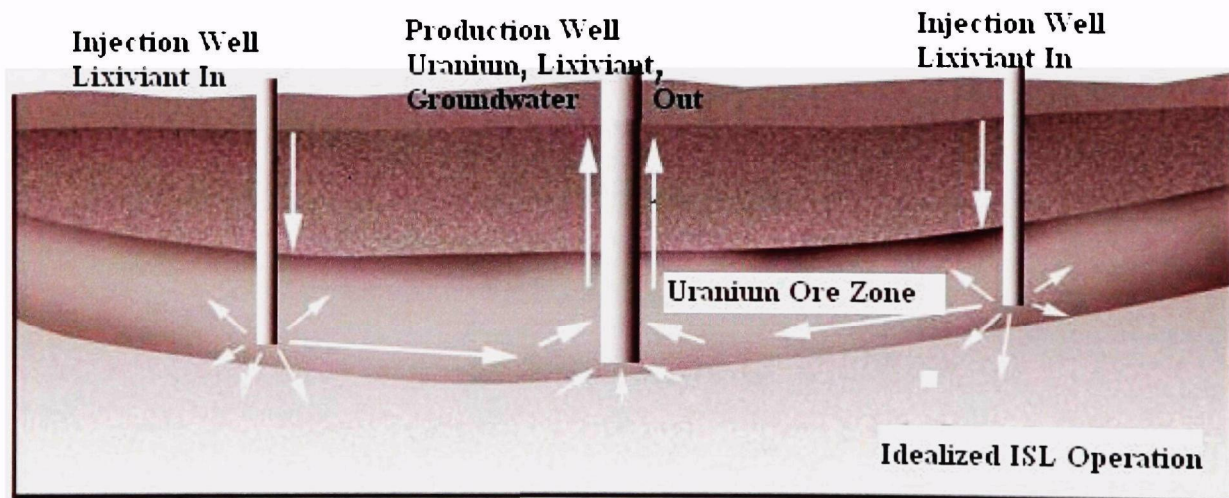
Source: Modified after ANAWA : http://www.anawa.org.au/mining/isl-diagram.html

When the ISL process is completed, the ore body and aquifer are placed in a restoration phase, as required by mine permits, NRC and Agreement State regulatory programs. Typically, the aquifer must be restored to background or EPA drinking water maximum contaminant limit levels where possible or practical, or to Alternate Concentration Limits (ACLs) in terms of the presence of metals, organics, pH level, and radioactivity, approved by the NRC and its Agreement States, with EPA concurrence. Therefore, in some cases, restoring it to the pre-operation level does not necessarily make it potable. EPA groundwater protection standards issues under authority of UMTRCA are required to be followed by ISL licensees of the NRC and its Agreement States. In addition to those requirements, ISL operators must apply for UIC permits from EPA. Through the UIC aquifer exemption process, EPA and its Delegated States determine if an aquifer or part of an aquifer is exempt from protection as an underground source of drinking water

during the mining process. Approval of this exemption is necessary before a UIC permit may be issued for ISL mineral extraction wells. EPA requires, however, that non-exempted groundwater sources be protected from contamination.

Uranium Milling

While not a central focus for this report, information is provided below primarily from U.S. EPA (1995a) on the uranium milling process; for more detailed discussions on the milling process, the reader is referred to that report. Licensed by the NRC under 10 CFR Part 40, Appendix A, mills process source materials (see Chapters 1 and Appendix VI) from conventional uranium mines and occasionally from other industrial activities or mines. Uranium mills have typically been associated with specific mines or functioned as custom mills, serving a number of mines. Most available information on milling operations was written when a dozen or more were operational, therefore the following discussions may not precisely describe milling activities being conducted at present, or in the future. The chemical nature of the ore determines the type of leach circuit required and, in turn, the extent of grinding of ore received from a mine.

The initial step in conventional milling involves crushing, grinding, and wet and/or dry classification of the crude ore to produce uniformly sized particles. Ore feeds from crushers to the grinding circuit where various mechanical mills grind the rock to further reduce the size of the ore. Water or lixiviant is added to the system in the grinding circuit to facilitate the movement of solids, for dust control, and (if lixiviant is added) to initiate leaching (U.S. DOI 1980). Screening devices are used to size the finely ground ore, returning coarse materials for additional grinding. The slurry generated in the grinding circuit contains 50 to 65 percent solids. Fugitive dust generated during crushing and grinding is usually controlled by water sprays or, if collected by air pollution control devices, recirculated into the beneficiation circuit. Water is typically recirculated through the milling circuit to reduce consumption (U.S. EPA 1983d).

After grinding, the slurry is pumped to a series of tanks for leaching. Two types of leaching have been employed by uranium mills, acid and alkaline. A solvent (lixiviant) is brought into contact with the crushed ore slurry. The desired constituent (uranyl ions) is then dissolved by the lixiviant. The pregnant lixiviant is separated from the residual solids (tails); typically the solids are washed with fresh lixiviant until the desired level of recovery is attained. The uranyl ions are recovered (stripped) from the pregnant lixiviant. The final steps consist of precipitation to produce yellowcake, followed by drying and packaging (Pehlke 1973). The stripped lixiviant may be replenished and recycled for use within the leaching circuit or as the liquid component in the crushing/grinding operation. Ultimately, the solids may be washed with water prior to being pumped to a tailings pond; this wash serves to recover any remaining lixiviant and reduce the quantity of chemicals being placed in the tailings impoundment. Wash water may be recycled to the lixiviant or to the crushing and grinding circuits.

Operational mills currently function independently of specific conventional mines and generate materials that are, in most cases, unique from those generated at the site of extraction. Under UMTRCA, source-handling licenses place specific requirements on the disposal of radioactive wastes; the design and construction of tailings impoundments address NRC requirements for permanent storage of these wastes. Radionuclide-containing wastes generated by ISL operations are typically shipped to tailings impoundments at mill sites. Figure 2.7 shows the general physical layout of a typical uranium mill.

Information on statutory requirements for closure and reclamation of abandoned and inactive uranium mills can be found in Appendix VI, characteristics of mill tailings in Chapter 3, and reclamation

procedures for closed mills and mill tailings impoundments can be found in Chapter 4. Mills in operation and inactive are discussed below.

Figure 2.7. Generalized Uranium Mill Physical Layout
*This figure shows how a uranium mill is physically set up to crush raw ore
into particles amenable to chemical treatments for extracting uranium.*
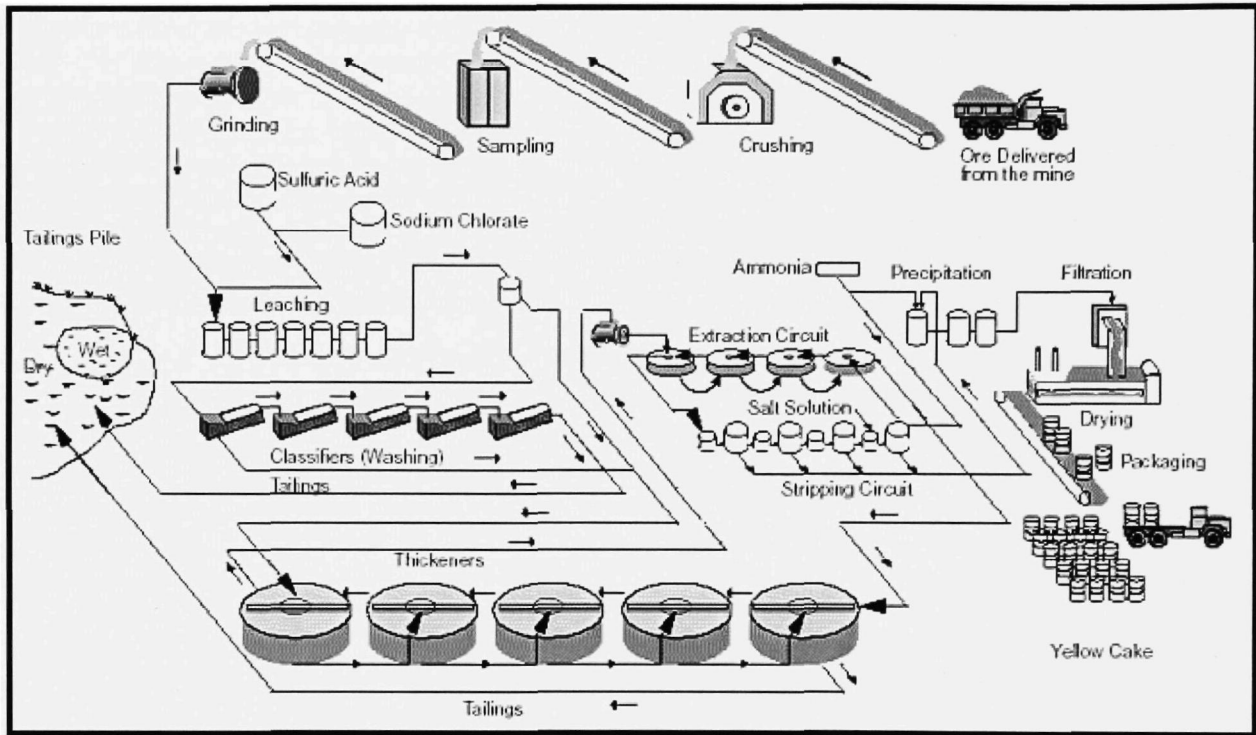
Source: U.S. DOE/EIA, http://www.eia.doe.gov/cneaf/nuclear/page/uran_enrich_fuel/uraniummill.html

The Uranium Industry Today

Due to worldwide oversupply of uranium, and dearth of new U.S. nuclear plants, the U.S. uranium mining industry was depressed from the early 1980s until about 2003, when only a few mines remained in operation. In 1981, the United States produced nearly 14,800 metric tons of oxide of uranium (U_3O_8) equivalent at an average price of over $34 per pound. U_3O_8 equivalent production in 1991 was approximately 3,600 metric tons sold at an average price of $13.66 per pound. While it had decreased to less than $8 per pound in 2000, by 2004, due to increasing demand, the price of uranium increased substantially. In early 2006, it had increased to approximately $40 per pound. These fluctuations in price affect the numbers of operating mines and mills in the country, and the methods of extraction used.

The employment structure in the uranium industry has significantly changed since the mid-1970s, when nearly 60 percent of the uranium industry labor force was devoted to uranium mining and production. This fraction steadily declined until recently, when only about 25 percent of the employment was related to mining (including ISL) and almost one-half of that was associated with reclamation of past production facilities. The industry experienced the highest level of employment in 1979 with 21,500 workers. In 1981 employment was about 13,600, and in 2000 the work force was down to 627 workers (U.S.

DOE/EIA 2001). Due to increased demand for uranium which resulted in higher prices, steady increases were seen in employment and production of uranium commencing in 2004.

The U.S. Department of Energy's EIA reports that in 1992, 51 person-years were expended in exploration, 219 in mining activities, 129 in milling operations, and 283 in processing facilities (U.S. DOE/EIA 1992, 1993). By 2000, one person-year was expended in exploration, 157 in mining, 106 in milling, and 137 in processing (U.S. DOE/EIA 2001); the remainder (226 person years) were involved in site reclamation. It is reported in the "Domestic Uranium Report" (U.S. DOE/EIA 2005b) released by the Department of Energy in August, 2005, that employment in the U.S. uranium production industry totaled 420 person-years, an increase of 31 percent from the 2003 total. Reclamation employment increased three percent. Wyoming accounted for 33 percent of the total 2004 employment, while Colorado and Texas employment almost tripled since 2003. Overall, $86.9 million went to drilling, production, land exploration and restoration activities in 2004.

A total of 17 uranium mines were operational in 1992: five conventional mines (both underground and open-pit), four ISL and eight reported as "other" (mill tails recovery operations, mine water extraction, or from low-grade stockpiles). Uranium in 1992 was also produced to a limited extent as a side product of phosphoric acid production at four sites (U.S. DOE/EIA 1993). By 2002, production had been reduced to three ISL operations and one underground mine (U.S. DOE/EIA 2003a). The ISL sites were located in Wyoming and Nebraska. A number of mines were closed and inactive with the possibility of reopening should the price of uranium increase in the future. In 2002, only 2.4 million pounds (~1090 MT) of U_3O_8 were produced domestically by: ISL operations, processing of waste mine-water, or reclamation and restoration activities at closed ISL sites.

The uranium production industry had a turnaround in 2004. An increase in all aspects of the industry was noticed for the first time since 1998. This included drilling, mining, production and employment. In 2004 (latest statistics available) 2.5 million pounds (~1135 MT) of U_3O_8 were mined in the U.S. which was 11 percent higher than the previous year (U.S. DOE/EIA 2005a). A new underground mine and a new ISL mine started in 2004. Total U.S. production of yellowcake (uranium concentrate) was 2.3 million pounds (~1045 MT) which was 14 percent higher than the production in 2003. Table 2.2 below provides U.S. uranium concentrate production by quarters.

Table 2.2. U.S. Uranium Mine Production: 2000-2005

This table shows Total Production of Uranium Concentrate in the United States, 2000 -2005
Production is reported in pounds U_3O_8, metric tons are included in parentheses

	2000	2001	2002	2003	2004	2005[P]
1st Quarter	1,018,683 (462 MT)	709,177 (322 MT)	620,952 (282 MT)	[E] 400,000 (181 MT)	[E] 600,000 (272 MT)	708,980 (322 MT)
2nd Quarter	983,330 (446 MT)	748,298 (339 MT)	643,432 (292 MT)	[E] 600,000 (272 MT)	[E] 400,000 (181 MT)	630,057 (286 MT)
3rd Quarter	981,948 (445 MT)	628,720 (285 MT)	579,723 (263 MT)	[E] 400,000 (181 MT)	588,738 (267 MT)	585,925 (266 MT)
4th Quarter	973,585 (442 MT)	553,060 (251 MT)	[E] 500,000 (227 MT)	[E] 600,000 (272 MT)	[E] 600,000 (272 MT)	NA
Calendar-Year Total	3,957,545 (1795 MT)	2,639,256 (1197 MT)	[E] 2,344,107 (1063 MT)	[E] 2,000,000 (907 MT)	2,282,406 (1035 MT)	NA

P = Preliminary data.
E = Estimate - The 2003 and 1st, 2nd, and 4th quarter 2004 production amounts were estimated by rounding to the nearest 200,000 pounds to avoid disclosure of individual company data. The 4th quarter 2002 production amount was estimated by rounding to the nearest 100,000 pounds to avoid disclosure of individual company data. This also affects the 2002 annual production.
NA = Not Available.

Notes: Totals may not equal sum of components because of independent rounding or reporting methods mentioned previously.
Next update is approximately 45 days after the end of the fourth quarter 2005.
Source: Modified from U.S. DOE/EIA (2005b): Form EIA-858, "Uranium Industry Annual Survey."

Only 16 percent of all uranium purchased by U.S. utilities in 2000 was domestically produced (U.S. DOE/EIA 2000a). According to surveys of owners and operators of U.S. civilian nuclear power reactors, future deliveries of U_3O_8 for 2001-2010 would amount to 116.5 to 179.0 million pounds (53 to 81 thousand MT). It was also estimated that foreign suppliers would provide 54 percent of the maximum projected deliveries through 2010.

U.S. non-conventional extraction facilities are primarily ISL plants. The decision to reopen a plant primarily depends upon the prevailing economics and market conditions. A few ISL operations are remaining open or inactive today, opening intermittently as the price of uranium continues to fluctuate. The only mills currently operating are Cotter Corporation mill in Colorado and International Uranium's White Mesa mill in Utah, while the Kennecott Sweetwater Wyoming mill is inactive, and the Plateau Resources mill in Utah is amending its license to operations (U.S. DOE/EIA 2005a).

Recent power uprates[3] and upgrades to U.S. nuclear plants have had the equivalent impact of nineteen new reactors starting operation, and other countries have indicated interest in building new plants as well. Since most of the demand for uranium originates from the commercial sector (nuclear power plants), and that demand is increasing, it is likely it will affect uranium market demand and supplies (Wyoming Mining Association 2004).

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[3] The process of increasing the maximum power level at which a commercial nuclear power plant may operate.

U.S. uranium reserves must also be taken into consideration, because changes in the price of uranium may make them important resources in the future. Figure 2.8 provides a map with locations of reserve areas, while reserve estimates are included in Table 2.3. Reserve estimates represent the quantities of uranium (as U_3O_8) that occur in known deposits, such that portions of the mineralized deposits can be recovered at specific costs under current regulations using state-of-the-art mining and milling methods (U.S. DOE/EIA 2004). At of the end of 2004, EIA estimated uranium reserves in the $30- and $50-per-pound categories were 265 and 890 million pounds (120 and 400 thousand MT), respectively. Underground mine reserves accounted for about one- half of the total reserves in each cost category. The reserve decreases are based on 2003 mine production of uranium and reflect the combined effects of depletion and erosion of in-place ore quantities remaining at year-end. Figure 2.9 below shows the status of mines, ISL operations, and mills in the U.S. as of late 2005.

Figure 2.8. Major U.S. Uranium Reserve Areas

This map shows major areas of remaining uranium reserves, all in the western U.S.

Major U.S. Uranium Reserves
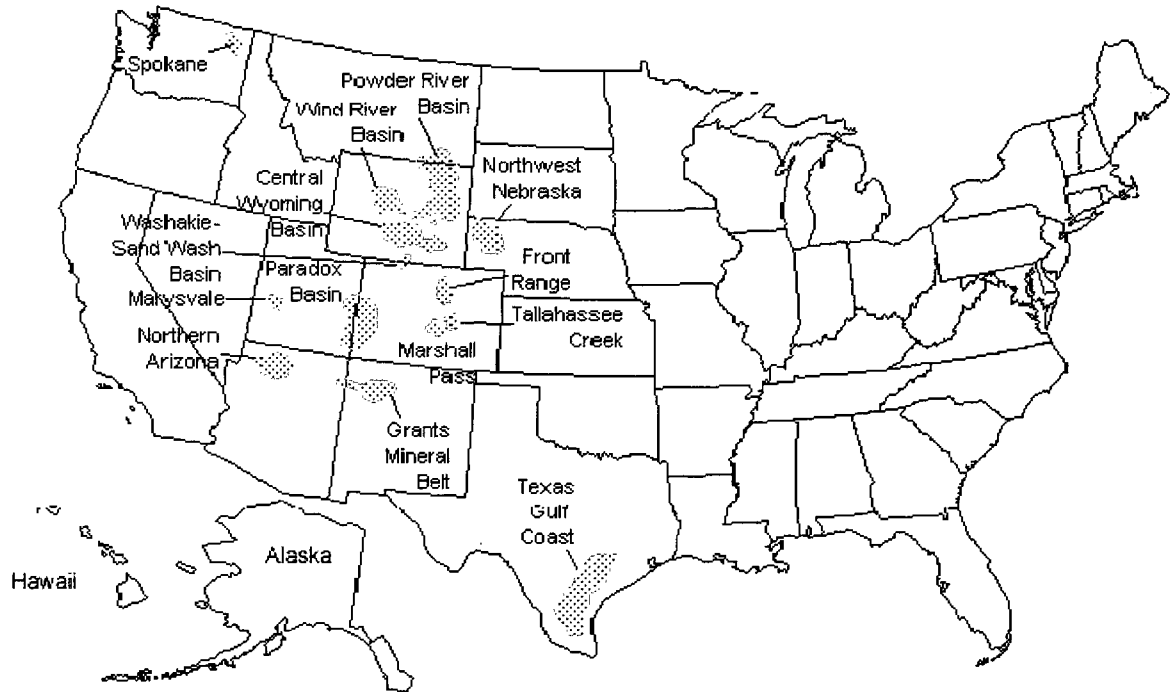
Sources: Based on U.S. Department of Energy, Grand Junction Project Office (GJPO), National Uranium Resources Evaluation, Interim Report (June 1979) Figure 3.2; and GJPO data files.

Source: From DOE/EIA http://www.eia.doe.gov/cneaf/nuclear/page/reserves/uresarea.html)

Table 2.3. Uranium Reserves of the United States as of December 31, 2003.

This table developed by the Energy Information Administration of DOE provides a breakdown of uranium reserves by mining method based on price of uranium of $30 per pound and $50 per pound.

U.S. Forward-Cost Uranium Reserves by Mining Method, December 31, 2003						
Mining Method	Forward-Cost Category					
	$30 per pound			$50 per pound		
	Ore in million tons (million Metric Tons)	Grade[a] (percent U$_3$O$_8$)	U$_3$O$_8$ in million pounds (Metric Tons)	Ore in million tons (million Metric Tons)	Grade[a] (percent U$_3$O$_8$)	U$_3$O$_8$ in million pounds (Metric tons)
Underground	25 (23)	0.272	138 (62,600)	143 (130)	0.163	464 (210,500)
Open-pit	10 (9)	0.139	29 (13,150)	163 (148)	0.079	257 (116,600)
In Situ Leaching	39 (35)	0.127	98 (44,450)	116 (105)	0.071	165 (74,800)
Other[b]	< 1 (0.9)	0.265	<1 (<453)	3 (2.7)	0.059	4 (1,814)
Total	**74 (67)**	**0.178**	**265 (120,200)**	**424 (385)**	**0.105**	**890 (404,000)**

[a]Weighted average percent U$_3$O$_8$ per ton of ore.
[b]Includes low grade material and miscellaneous.

Notes: Uranium reserves that could be recovered as a byproduct of phosphate and copper mining are not included in this table. Reserves values in forward-cost categories are cumulative: that is, the quantity at each level of forward-cost includes all reserves at the lower costs. Totals may not equal sum of components because of independent rounding.
Sources: Estimated by Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, based on industry conferences; U.S. Department of Energy, Grand Junction Office, files; and Energy Information Administration, Form EIA-858, "Uranium Industry Annual Survey," Schedule A, Uranium Raw Material Activities (1984-2002) and Form EIA-851A, "Domestic Uranium Production Report" (2003).

Source: Modified from U.S. DOE/EIA (2005c), http://www.eia.doe.gov/cneaf/nuclear/page/reserves/uresmine.html

Figure 2.9. Status of Mines, ISL Operations, and Mills in the U.S. as of November 2005
*This figure shows the locations and operating status of uranium operations in the U.S.
as of the end of 2005. An increase in the price and demand for uranium resulted
in the re-opening of some conventional uranium mines and ISL operations,
and decisions to re-start some sites which were undergoing closure.*

Approximate Locations of Operating, Standby, or Pending Uranium Mills and Mines
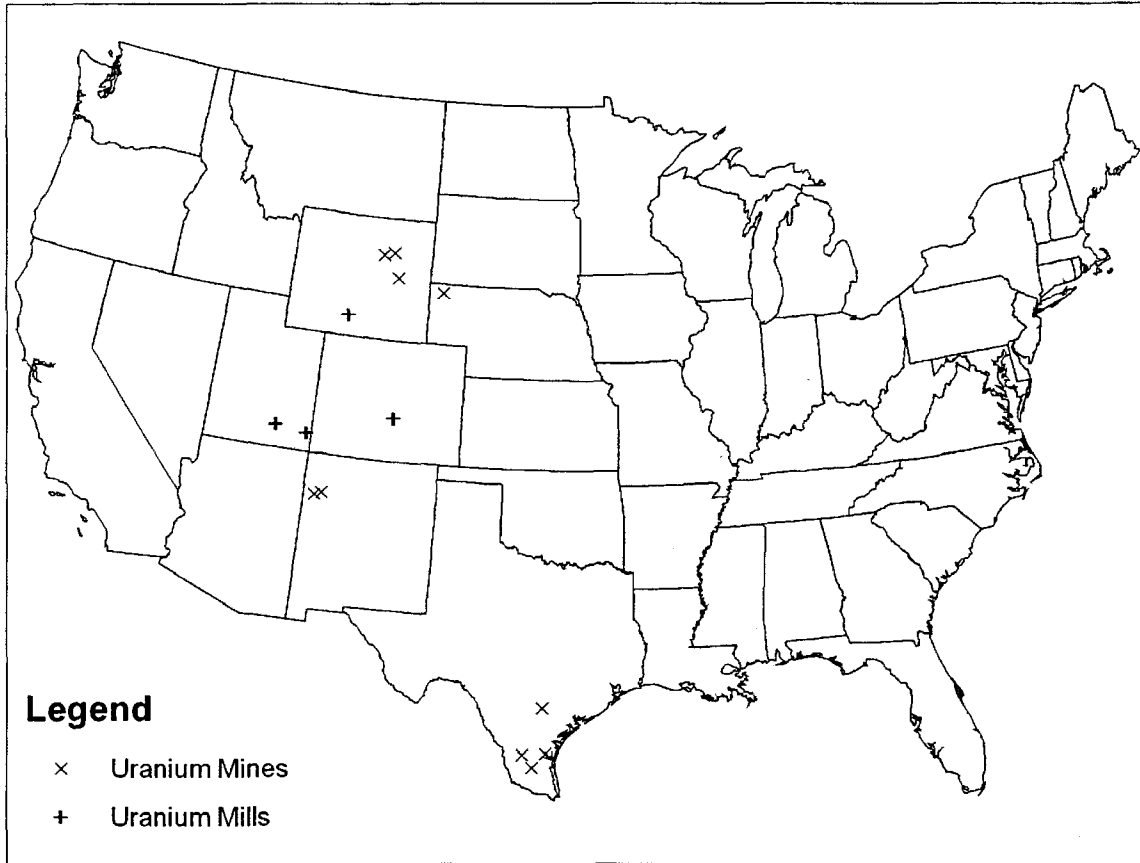
Source: U.S. EPA.

Chapter 3. Volume and Characteristics of Uranium Mine Wastes

Uranium has been found and mined in a wide variety of rocks, including sandstone, carbonates[1], and igneous (volcanic-derived) rocks (see Chapter 1). This variety of source material, the type of mine and extraction operation (see Chapter 2), local climate, soil, and topography can lead to a wide range of differing physical and chemical properties in waste materials. Waste characteristics are important because they are used to model and assess the environmental impacts and public health risks of radionuclides, heavy metals, and other chemicals associated with mine sites, and the implications for site cleanup. While this chapter discusses wastes from conventional mining, solution extraction, and milling of uranium, a principal focus of this report is TENORM from conventional mining, and in particular, wastes from abandoned mines that have not been reclaimed, or which may need future reclamation.

When uranium mining first started, most of the ores were recovered from deposits located at, or near the surface of the land. Ores were often exposed at the surface, and underground mines followed mineralized zones directly into the subsurface. Thin overburden over deeper parts of the ore body adjacent to the surface exposure would be removed to create shallow open-pits. As easily accessible ore deposits became depleted, mining had to be performed at increasing depths by either open-pit or underground methods. To reach deeper deposits, the industry had to move larger quantities of topsoil, overburden, plus barren or waste rock.

The amount of overburden that may be removed during open-pit mining is a complex function of the depth to the ore body, the grade and thickness of the ore bearing zone, the price of uranium, and the costs of moving the overburden and site restoration. The costs of processing ore at mills also influence the overall economics of underground and surface mining. These costs have steadily declined, and have lowered the ore grade that is economically feasible to extract (Otton 1998). Thus, while an ore grade of 0.15 percent was often ignored in the early mining years, newer, more efficient ore extraction techniques have targeted ore grades as low as 0.03 percent, though that is an extreme case. The NRC has established a level of 0.05% uranium content as a threshold for regulation as source material under its regulations 10 CFR 40.4; NRC considered technology and economics in selecting the threshold.

Waste terms that will be used in the discussions from Chapters 3 through 5, and the Appendices, are listed in Table 3.1 and are defined below in the text, as well as the Glossary (Appendix I). Wastes considered to be TENORM, versus those subject to NRC or its Agreement States' byproduct regulations are also identified.[2]

While there is a limited discussion in this chapter on environmental fate and transport of uranium associated with mine wastes, the reader is referred to previous EPA reports on uranium geochemistry (U.S. EPA 1999b and 1999c). The geochemistry of uranium can be extremely complicated, however, those documents provide an overview of important aqueous and solid phase parameters, as well as

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[1] A sediment or sedimentary rock formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron; e.g., limestone and dolomite.

[2] Some materials that are wastes within the plain meaning of the word are not "solid wastes" as defined under the Resource Conservation and Recovery Act and thus are not subject to regulation under that law. These include, for example, mine water or process wastewater that is discharged pursuant to a National Pollution Discharge Elimination System permit. It is emphasized that any questions as to whether a particular material is a waste at a given time should be directed to the appropriate EPA Regional office.

discusses general geochemistry, aqueous speciation, precipitation and co-precipitation, and other important geochemical aspects.

Data obtained from many older scientific studies referenced in this report may have only been originally provided in English measurement systems. Conversions are made in the text and tables of this report; however, the reader should understand that the converted numbers may be rounded. If available in the original studies cited in this report, information on uncertainties and precision of measurements and data will be included. However, many of these studies were conducted during a time when reporting uncertainties and precision of data were not standard practice. While data quality is a vital aspect of scientific and technical endeavor, we regret that the boundaries of uncertainty and accuracy of data presented may not have been cited in many of the original studies available for this study.

Table 3.1. Uranium Mine and Operations Wastes

The following mine wastes are generated by conventional uranium mines, heap leach and ISL operations, and uranium mill operations. They are the principal wastes discussed in Chapters 3 through 5, and the Appendices of this report. Not all wastes listed may be radioactive at all uranium mines or operations, though if they are, they may be subject to regulatory control according to the column they are listed under.

Wastes Generated by Uranium Mines and Extraction Operations		
Conventional Open-Pit and Underground Mines (TENORM Wastes—EPA, Federal Land Management, and Tribal and State Agencies Jurisdiction)	Heap Leach and ISL Operations (Byproduct Wastes subject to NRC and Agreement State Jurisdiction)	Uranium Mills (Byproduct Material Subject to NRC or Its Agreement State Jurisdiction)
Protore*		
Overburden*		
Barren or Waste Rock*		
Top Soils*	Top Soils*	
Drill Cuttings* and Drilling Wastes	Drill Cuttings* and Drilling Wastes	
Wastewater	Wastewater	Wastewater
Wastewater Treatment Sludge	Wastewater Treatment Sludge	Wastewater Treatment Sludge
Lab Wastes	Lab Wastes	Lab Wastes
Pit Water*		
Mine Water	Produced Water	
	Leachate	
	Liquids from aquifer restoration	
Evaporites	Evaporites	Evaporites
		Mill Tailings
Refuse (if radioactive)	Refuse (if radioactive)	Refuse (if radioactive)

Source: U.S. EPA (1983a,b,c; 1995), U.S. NRC (2004, 2003)
*Term was previously defined in Chapter 1.

Terms in Table 3.1 not previously defined:
- *Drilling wastes*—Wastes associated with a drillhole operation at a mine or extraction facility that are not considered cuttings or cores. May include drill muds or other drilling fluids, sludges, or evaporation products collected in excavated pits from wastewater produced during drilling.
- *Wastewater*— The spent or used water from a mine that contains dissolved or suspended matter.
- *Wastewater Treatment Sludges*—Sludge derived by the treatment of wastewater to remove suspended solids, metals, radionuclides or other pollutants from mine generated wastewater.
- *Lab Wastes*—Wastes of any kind generated by a laboratory, usually on-site, analyzing rock,

sediment, water or other samples obtained at the mine or extraction facility, or its vicinity.
- *Mine Water*— Water or brine which collects in mine workings, both surface and underground, as a result of inflow from rain or surface water and of groundwater seepage.
- *Produced Water*— Water from ISL operations extracted from the subsurface with dissolved minerals. It may include water from the reservoir, water that has been injected into the formation, and any chemicals added during the production/treatment process.
- *Leachate*—A solution obtained by leaching; e.g., water that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution.
- *Evaporite*—A chemical sediment that precipitates when the salty water in which it had dissolved evaporates
- *Refuse*—Solid waste. Insoluble materials ranging from municipal garbage to industrial wastes that contain complex and sometimes hazardous substances. Solid wastes also include sewage sludge, agricultural refuse, demolition wastes, mining equipment and mining residues. Solid waste also refers to liquids and gases in containers.
- *Mill Tailings*— Residue of raw material or waste separated out during the processing of uranium mineral ores. Byproduct material in accordance with the AEA.

Waste Footprint of a Mine

Though all mining methods produce waste products, the volume, location, state, and environmental impacts of these wastes can be vastly different. For example, open-pit and underground mining techniques, known as conventional mining, generally produce large amounts of solid waste, while ISL methods produce only small amounts of solid waste, but result in more significant amounts of liquid waste that can spread across a very large area. As noted previously and in Appendix VI, ISL operations and liquid wastes generated by those activities, and their environmental impacts are regulated by the NRC or its Agreement States. In general, states, Tribes, and federal land management agencies are responsible for regulating the disposal of solid and other waste generated on their lands by mining operations.

The overall footprint of a mine area may be described as the areal extent of land physically disrupted by a mine operation. The footprint can vary significantly depending on the amount of waste left on site, and not necessarily to the amount of oxide of uranium (U_3O_8) produced. The typical waste footprint of uranium mining operations has changed since the late 1940s—from very small, to very large, and then smaller again.

Because the nature of mining changed over the years, waste generation also changed. This change in waste generation largely reflects changes in the scope of mining operations and the technology employed. When early mining efforts in the 1940s and 1950s were dominated by small operations, sometimes consisting of a single prospector/miner, thousands of mines were developed from ore bodies of the Colorado Plateau, sometimes as small as a single rich uraniferous vein or lens weighing as little as a few metric tons. The early small mining endeavors generated small quantities of waste, because miners found and exploited only deposits near the surface, and they had limited capacity to move large quantities of material. These small quantities of waste typically were discarded within several to 100 yards (about several to 100 meters) of the mine opening or pit.

As many mining properties both on the Colorado Plateau and in areas in other states, such as Texas and Wyoming, proved to have much larger ore bodies, more expansive mining operations developed at these sites. When larger companies came on the scene in the 1950s and 1960s, they brought technologies and

manpower to exploit larger ore bodies, deeper in the ground, and of lower grade. These large conventional operations generated correspondingly large waste streams, and the overall site size expanded significantly.

Major open-pit mines tend to disturb large surface areas from the extent of both the pit and the mine waste areas. Generally, tens to hundreds of acres may be covered by stored overburden. For example, an aerial survey conducted of eight surface mining sites in New Mexico and two in Wyoming indicated that disturbed areas varied from just under three to 380 acres (approximately one to 154 hectares), with an average of 110 acres (approximately 45 hectares) per site (U.S. EPA 1983b). At some sites, as mining progressed, the overburden was used to backfill mined-out areas of the open-pit in anticipation of later reclamation. Most of the older surface mines (pre- to mid-1970s) were not backfilled during mining operations, while some of the more recent mining included modest backfilling operations.

The surface area affected by major underground mining activities generally involves less than about 50 acres (20 hectares). Mine maps often show extensive underground mining following ore zones with only small piles of waste rock at the mouth of the mine's entry. For example, an aerial survey conducted of nine underground mining sites located in New Mexico and one in Wyoming indicated that disturbed surface areas varied from just over two to 42 acres (one to 17 hectares), with an average of 30 acres (approximately 12 hectares) per site (U.S. EPA 1983b). However, the underground mine works (or tunnels) may extend laterally for more than a mile in several directions. The Orphan Mine (see Appendix III) is an underground mine with a surface loading area clearing less than five acres (two hectares), and a cliffside mine opening covering similar acreage, where spoil rock and a collapse hole over the abandoned tunnels are the principal observable features.

When economics and technological advances in the 1980s prompted the increased use of ISL as an extraction method, the volume of solid waste generated dropped dramatically. While not a surface mining method, for comparison purposes only, the total areal extent of an ISL operation may be large, depending on how drill holes are situated, and how extensive evaporation ponds are. To be cost-effective, ISL requires large production areas or zones, but the surface facilities may take up only a small portion of the acreage. Table 3.2 presents the general features of several ISL operations (U.S. EPA 1993b). The number of production areas ranges from one to seven and can include a large number of wells, ranging from 200 to over 10,000, while aquifers are often located both above and below production zones.

Table 3.2. Profile of Several Texas ISL Uranium Mining Operations

The acreage of ISL operation properties varies from about 200 to over 6,000 acres (81 to 2,430 hectares). The actual acreage covered by well fields may be significantly less (Kennecott Uranium Company 2004). ISL operations are not a surface mining method, though the production facilities may produce from large land holdings, and are regulated by the NRC or its Agreement States. All the facilities included below are in Texas.

Mine Name	Acreage
Benavides	170
O'Hern	270
Zamzow	316
Pawnee	320
West Cole	680
West Clay	884
Lamprecht	957
Boots Brown	1,025
Pawelek	1,698
Holiday	2,000
El Mesquite	2,200
Rosita	2,208
Burns Moser	2,262
Kingsville Dome	2,315
Trevino	5,750
Talan Gara (renamed Palangana)	6,272

Source: U.S. EPA 1993b

Mine Waste Volumes

Conventional Open-Pit and Underground Mines

In open-pit mining, as described in Chapter 2, a pit is excavated to expose the uranium deposit. After the topsoil is removed and stockpiled nearby, the overburden is removed and trucked to a nearby mine waste area. Occasionally, dikes and ditches are constructed around these waste piles to collect runoff and divert it to sedimentation ponds.

While underground mining is much less disruptive to surface terrain than open-pit mining and produces less waste, that waste may have higher average radioactivity. In underground mining, access to the ore body is gained through one or more adits or vertical shafts, generally sunk to a slightly greater depth than the ore body, or through inclines and declines, all of which are cut through barren or waste rock. Mining carefully follows the ore body using stopes and tunnels to minimize the amount of waste material that must be moved. When mining in larger deposits, other mining methods may be used, for example, the room and pillar or block caving techniques. The block caving technique forces a large section of ore deposit to fall into a man made cavern. The ore is broken by drilling and blasting, and ore and waste rock are moved out of the mine to the surface through tunnels, inclines, and shafts. The barren or waste rock is removed to a spoils area that may be surrounded by a ditch to contain water runoff.

Data from the U.S. Department of Energy's (DOE's) Energy Information Administration (EIA) indicate that before 1980 about one-third of conventional uranium mines were small with less than 100 metric tons of uranium ore production, about one-fifth to one-quarter of the mines were moderate sized with between 100 and 1,000 metric tons of production, and about one-third of the mines were large and had production between 1,000 and 100,000 metric tons of production (U.S. EPA 1983b). Only about five percent, or 150–220 mines, were extremely large mines producing more than 100,000 metric tons of ore. When combined with information on the relationship between ore production and waste, it is possible to estimate the amounts of waste for the different production categories.

To calculate an estimate of waste generation, waste-to-ore ratios are needed for different sizes of mines. Throughout the 1950s, 1960s, and 1970s, open-pit mining on the Colorado Plateau was characterized by small to moderate-sized operations with highly variable waste-to-ore ratios, but the data on these mines are not good and waste estimation is difficult. The higher the waste-to-ore ratio, the more waste that is generated per ton of ore extracted. Large open-pit mines in Wyoming and New Mexico usually had lower waste-to-ore ratios, and in Texas moderate to large open-pit operations were found with generally high waste-to-ore ratios. In the late 1970s (Bohert and Gerity 1978; Facer et al. 1978) and early 1980s, waste-to-ore ratios for the largest mines appear to have peaked at an average of about 30:1 (30 times as much waste as ore produced). As the price of uranium decreased in the early 1980s, only the more efficient open-pit operations remained in production, and the waste-to-ore ratios also decreased for the period 1984 to 1992.

For underground mines, waste-to-ore ratios generally range from 20:1 to 1:1, with an average ratio of about 9:1 (nine times as much waste as ore produced) (U.S. EPA 1983b). As with surface mining, this ratio has also changed over the years with increased mining efficiency, and selection of more economically produced deposits such that the amount of waste decreased from a range of 5:1 until the early 1970s, to about 1:1 by the late 1970s.

EIA historical records (Smith 2002) indicate that before 1980, a number of underground and surface uranium mines generated less than 1,000 metric tons of ore with a ratio of waste to ore ranging from about 10:1 to 30:1. Accordingly, a 1,000 metric ton mine might generate 10,000–30,000 metric tons (3,500–11,000 cubic meters) of waste. With respect to the area covered by waste piles, for EIA's two smallest production size categories, less than one-third of an acre would be expected to be covered by waste piles 16 feet (five meters) high. Smaller mines could have a waste-to-ore ratio of 50:1. At 16 feet (five meters), which is an average height for a waste pile, a small operation could produce waste covering 0.2–0.5 acres (0.08 to 0.20 hectares). Waste piles for small surface and underground mines were found to cover 0.1 to five acres (0.04 to two hectares) (U.S. EPA 1983b).

To estimate the volume of waste that may have been generated, Otton (1998) conducted a study of mine waste ratios for EPA. Table 3.3 presents the study results for surface and underground mining. Appendix IV provides the basis for the estimates. Waste produced by open-pit mining is a factor of 45 greater than for underground mining, based on their respective averages. For the range between the low and high estimates, the factor is 190 for the low estimate and 80 for the high. Thus, the amount of overburden generated from open-pit mines far exceeds that of underground mines.

Table 3.3. Estimated Overburden Produced by Open-Pit and Underground Mining

The waste generated by open-pit mining is estimated to be 45 times greater than for underground mining.

Mining Method	Estimated Overburden Produced (MT)		
	Low Estimate	High Estimate	Average
Surface Mining	1,000,000,000	8,000,000,000	3,000,000,000
Underground Mining	5,000,000	100,000,000	67,000,000

Source: Otton 1998.

Waste Volumes at Sample Conventional Mines

Typically, the waste material is placed in piles that can be quite large, representing thousands to hundreds of thousands of tons of material and covering a large area. The White King/Lucky Lass mines site (two mines adjacent to one another—see Appendix III), now a Superfund site, had very large piles of waste material and protore. At the White King Mine one (protore) pile covers approximately 17 acres (seven hectares) with an average thickness of 20 feet (six meters), and a second (overburden waste) pile covers approximately 24 acres (about ten hectares) with an average thickness of 15 feet (about five meters) (U.S. EPA 2001a). Approximately 35,000 cubic yards (32,000 cubic meters, assuming 2,800 kg/m^3 waste material density due to the high concentration of denser uranium in the material)[3] of soil outside the perimeter of the White King piles were estimated to be elevated in radium (defined as > 5 pCi/g (0.185 Bq/g) Ra), along with 7,700 yards^3 (7,040 m^3) of soil outside the perimeter of the Lucky Lass piles.

The Jackpile-Paguate open-pit mine began production in New Mexico in 1953 and ceased in 1982. Table 3.4 demonstrates how the ratio of overburden to produced ore changes over the life of a mine. The mine site contained 32 waste dumps and 23 protore dumps segregated according to grade. About 10.5 million metric tons (MMTs) of protore were stored outside the pits, and another 4.5 MMTs were stored in dumps within pits. The ratio of all waste to protore was about 24:1. About 92 MMTs of backfill, comprised of ore-associated waste and some overburden, were returned to the pits during operations.

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[3] Density is an important factor in calculating the metric tons (weight per volume) of waste rock.

Table 3.4. Changing Ratio of Overburden to Ore Over Mine Life—Jackpile-Paguate Mine, New Mexico

The amount of mine waste increases over time relative to the amount of produced ore in a large surface mine. Ore and overburden are report in metric tons (MTs).

Year	Ore Produced (MTs)	Overburden (MTs)	Mining Ratio (overburden protore rock : ore)
1953 - 1963	6,000,000	70,000,000	11.7:1
1953 - 1974	9,000,000	110,000,000	12:1
1953 - 1982	23,000,000	364,000,000	16:1

Sources: Kittel 1963; Graves 1974; U.S. BLM 1986.

At the other end of the spectrum is the Canyonlands National Park in Utah (see Appendix III), where the waste dumps for underground mines (most likely either exploration shafts or small mines) ranged from 35 to 800 yards^3 (37 to 612 m^3) (Table 3.5). Production data from these mines were unavailable. Figure 3.1 shows the outside of one of the mine openings.

Table 3.5. Mine Workings and Associated Waste Rock Volumes in Canyonlands, Utah

This table highlights the variety of waste dump sizes and lengths of entries for a series of 12 closely located underground mines in Canyonlands National Park, Utah.

Workings vs. Waste	Mine											
	1	2	3	4	5	6	7	8	9	10	11	12
Lateral workings *in feet (meters)*	82 (25)	28 (9)	75 (23)	865 (264)	450 (137)	230 (70)	215* (66)	188 (57)	20 (6)	70 (21)	40 (12)	235 (72)
Waste *in yards³ (meters³)*	120 (92)			800 (612)	470 (359)			220 (168)	35 (27)	165 (126)	100 (76)	400 (306)

* Visual estimate of adit length. Remote workings are flooded 115 feet (35 meters) in from the portal.
Source: Burghardt et al. 2000.

Figure 3.1. Mine Portal, Canyonlands National Park, Utah
*Canyonlands, Utah, underground mine entry and the mine waste spoil pile located
on the canyon slope beneath. Note the coarse nature of materials
in the waste pile—boulders and cobbles, in addition to finer-grained materials.*
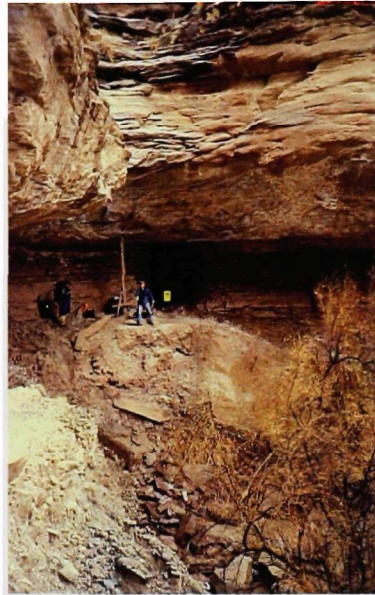
Source: Photo courtesy of Utah Division of Abandoned Mine Lands Reclamation

ISL Operations

Surface facilities and uranium extraction at ISL operations are regulated by the NRC or its Agreement
States; liquid and solid wastes produced are considered to be byproduct materials under the AEA. In
general, ISL operations generate small amounts of surface solid waste comprised of: (1) soil and
weathered bedrock material disturbed during surface preparation of the site, (2) waste from drilling of
injection and production wells, and (3) solids precipitated during the storage and processing of fluids in
holding ponds. The site surface preparation may include site grading for placement of temporary
structures, construction of access roads to well sites, laying of pipelines, and construction of well pads.
Disturbance of the site may make these surface materials more likely to be windblown, but the disturbed
material would likely have background radionuclide concentrations typical of levels present at the site
before the mine's development. Drilling wastes include drilling muds, water, chemicals, and drill cuttings
from the underground rock formations (Figure 3.2). These wastes are typically deposited in pits on site,
which are subsequently buried during reclamation. Some slight radioactivity may occur in accumulated
solids in the pit bottoms.

Leachate solutions circulating in the formation mobilize uranium and in some instances a part of their
associated uranium decay products. Alkaline leach and ammonium bicarbonate solutions at sites remove
about 15 percent of the radium in the uranium ore body (Brown 1978). More current solution mining
techniques make use of dissolved oxygen and carbon dioxide. The amount of radium and other uranium
decay products removed by these more recently used solutions is not known.

Liquid wastes from ISL operations are generated from three sources: (1) well field development, (2) processing plant operations, and (3) aquifer restoration activities. Limited data are available on the volume of this material. Options for the disposal of liquid wastes include solar evaporation ponds or deep-well injection. Land application is not an approved method of radioactive liquid waste disposal.

EPA studied sites for this report using data in NRC and State of Texas files, as well as site visits in Texas and Wyoming. For information purposes only, radionuclide data for ponds and injection wells collected for this report can be found in Appendix V. Descriptions of ISL fields studied are included in Appendix III.

Based on information collected, operators typically used numerous ponds for holding or disposing of produced water and brines (Figure 3.3). They ranged from 50 acre-feet (Irigaray) to 558 acre-feet (Highlands) per pond. In many cases, this water was eventually disposed of in deep-injection wells or was allowed to evaporate. In the case of evaporation, Crow Butte Resources estimated its operation would have generated 1,315 cubic yards (902 cubic meters), or eight acre-feet, of solid waste by mid-2000. NRC permitted that and other operations, such as Cogema's Christensen Ranch and Irigaray mines, to dispose of these wastes off site in byproduct tailings impoundments at other uranium-producing facilities. Available data are insufficient to estimate the total amount of solid and liquid wastes generated by existing and previous ISL operations.

Figure 3.2. ISL Operation Drilling Site
In this photo taken at a Wyoming ISL field, a truck-mounted rig is drilling a well. Top soils moved to level the site for drilling can be seen in front of the tank truck on the right of the picture. The soils must be used to restore the site after production is completed in accordance with Wyoming Department of Environmental Quality requirements.
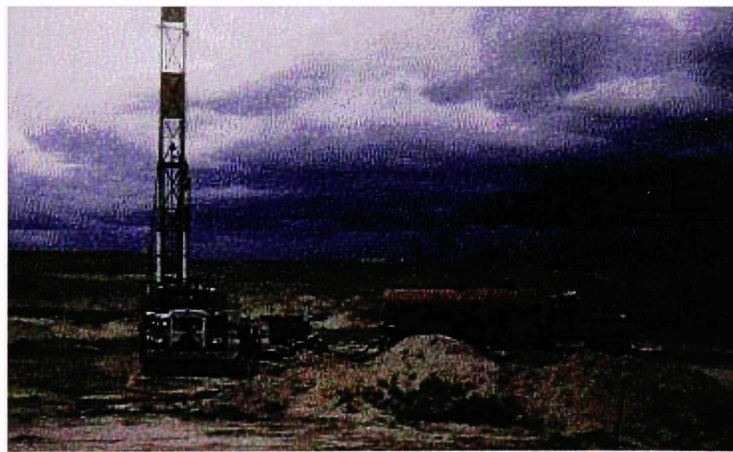
(Photograph by Mark Schuknecht, U.S. EPA)

Figure 3.3. ISL Evaporation Pond
This Wyoming ISL operation has a modern liner to prevent contaminated waters from leaching into the ground.

(Photograph by Mark Schuknecht, U.S. EPA)

Physical Characteristics of Uranium Mine Wastes

The characteristics of overburden and barren or 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. Knowing the rock types present is important for constructing risk model inputs, evaluating environmental impacts, and determining the most effective means of site reclamation. Common rock types found in mines from New Mexico, Texas and Wyoming include a wide variety of sedimentary, metamorphic, and igneous rock types (Table 3.6).

Table 3.6. Examples of Waste Rock Types Found
at Uranium Mines in Selected States

*The characteristics of overburden and barren or 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.*

State	Sedimentary Rock Types	Metamorphic and Igneous Rock Types
New Mexico	Sandstone, siltstone, shale, claystone, limestone, unconsolidated silt, clay, gravel	
Wyoming	Sandstone, siltstone, shale, claystone, limestone, coal, unconsolidated silt, clay, gravel	
Texas	Sandstone, siltstone, shale, claystone, limestone, coal, unconsolidated silt, clay, gravel, volcanic tuffaceous silts, volcanic ash	
Oregon (Lucky Lass/White King case study)		Rhyolite, tuff breccia, basalt
Washington (Midnite Mine case study)		Mica phyllite, mica schist, hornfels, marble, quartzite, calcareous silicates, quartz monzonite, granitic intrusives

Sources: U.S. EPA 1983a,b,c; 2001a.

Overburden from surface mines can include huge boulders that may have been broken down with explosives and heavy machinery into particles down to a micrometer (μm, one-millionth of a meter) in diameter (U.S. EPA 1983b). Table 3.7 presents the size distributions provided in a study of rock overburden from an unidentified Pennsylvania mine.

Table 3.7. Overburden Particle Size Distributions, Pennsylvania Mine
*Overburden from surface mines can range in size from a micrometer
to a meter or more in diameter.*

Particle Size (μm)	Weight (%)
> 2,000	75
50–2,000	13
2–50	8
< 2	4

Source: Rogowski 1978.

Overburden test pits at the Midnite Mine were excavated to depths ranging from 10 to 14 feet (three to four meters) (URS 2002). In general, the test pits encountered coarse-grained materials consisting of sand, gravel, cobbles, and boulders, while one test pit encountered clay from a depth of eight feet (two meters) to the bottom of the pit (14 feet or four meters). The wide range of grain sizes of the materials

encountered in the test pits and the presence of open void space indicate the highly heterogeneous nature of the waste rock.

Size gradation tests of individual test pit samples indicated gravel (5–65 percent), sand (21–43 percent) and silt and clay (or fines) (11–29 percent), showing great heterogeneity across the mine site. The moisture content of the waste rock material generally ranges from two to nine percent, with two samples as high as 23 percent. The specific gravity ranges from 2.75 to 2.84.

The White King/Lucky Lass Superfund site in Oregon (see Appendix III) has a large protore stockpile and a large overburden pile (Table 3.8). For all mines sampled, particle sizes for protore materials are the same as found with overburden and ore piles (EPA 1983b). Because unreclaimed rock piles are not stabilized, they can serve as sources of pollution, primarily through wind and water erosion. Fine particulates in general are susceptible both to aerial suspension and to transport in water as both suspended and dissolved solids in precipitation runoff.

Table 3.8. White King/Lucky Lass Mine Protore and Overburden Characteristics
Waste pile sizes are shown in acres (hectares) and cubic yards (cubic meters).

Stockpile Type	Protore	Overburden
Area	17 acres (7 hectares)	24 acres (10 hectares)
Volume	542,000 yards^3 (408,000 m^3)	408,000 yards^3 (307,000 m^3)
Thickness range	8–27 ft (2–8 m)	7–33 ft (2–10 m)
Type of material	Gravel, silt, clay layers, gravel at surface	Gravel at surface, sand and clay below, though more clay-like

Source: U.S. EPA 2001a.

Radionuclide leaching primarily from mine waste piles adjacent to open-pit mines—but also possibly derived by leaching from mine pit walls or by groundwater infiltration from underlying uranium deposits—can result in significant concentrations of radionuclides in water-filled pit lakes. Appendix V includes data on radionuclide concentrations found in numerous pit lakes and streams associated with open-pit mines.

The Yazzie-312 Mine (see Appendix III) is an example of a small surface mine that had a number of both protore and overburden waste piles located adjacent to the mine pit, which had filled with water. Runoff from precipitation over a 40-year period carried fine-grained materials back into the pit. The original pit was 40 feet (12 meters) deep, but infilling by runoff had left the pit only five feet (1.5 meters) deep as of 2001 when the mine underwent reclamation. Suspended sediment of clays and silts pervaded the pit water, leaving it a milky white color. Analyses (Panacea 2002) of 10 samples of pit lake water showed the following average contaminant concentrations: Total Uranium 173 pCi/L, Total Radium 2 pCi/L, and Total Thorium < 1 pCi/L. More information on overburden and protore wastes at this site can be found in the section in this chapter on Heavy Metals in Mine Wastes.

Figure 3.4a below shows a picture of one of the several overburden piles, while Figure 3.4b shows a picture of the pit lake.

Figure 3.4a. Overburden Pile at Yazzie-312 Open-pit Mine, Navajo Reservation, Arizona
Fine-grained overburden materials are found adjacent to the Yazzie-312 Mine in Cameron, Arizona.
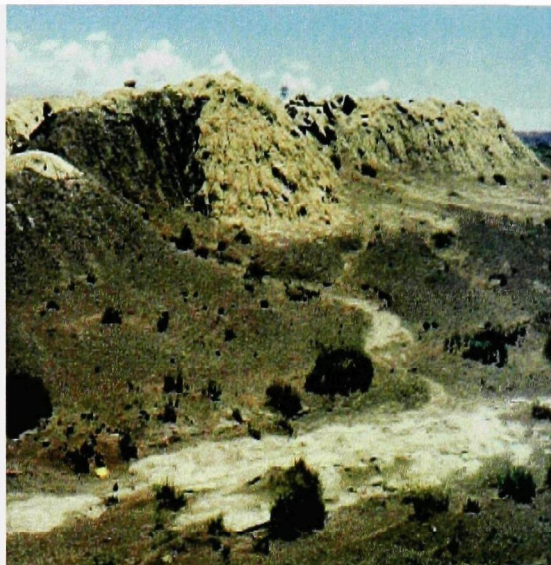
(Photograph by Loren Setlow, U.S. EPA)

Figure 3.4b. Pit Lake at Yazzie-312 Open-pit Mine, Navajo Reservation, Arizona
Football field size water filled open-pit mine. The original pit was 40 feet (12 meters) deep, but infilling by runoff had left the pit only five feet (1.5 meters) deep as of 2001 when the mine underwent reclamation.
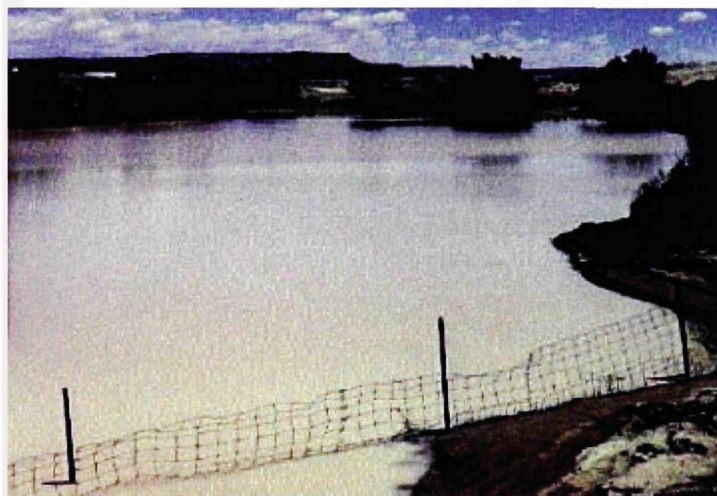
(Photograph by Loren Setlow, U.S. EPA)

Wastes from underground mines are much smaller than overburden piles generated by surface mines, and tend to be located near the mine entrances. When the land near the mine is relatively flat, the waste piles are dome shaped. In contrast, if the mine is located along a canyon rim or other steep elevation, the wastes form thin sheets extending beyond the mine entrance. The wastes consist of protore and barren or waste rock, and the protore may generally be found on top of the mine waste rock. The Canyonlands waste piles

described previously in Table 3.5 and Figure 3.1, and the description of the Orphan Mine (in Appendix III) provide examples of mine wastes from underground mines.

Potential for Water Contamination

Uranium mines are located throughout the West. Surface and underground mines have varying potential to contaminate aquifers and surface water depending on the meteorological, hydrologic, and geologic site characteristics. As mentioned previously, EPA has published comprehensive reports on uranium geochemistry with detailed discussions on fate and transport of uranium in the environment (U.S. EPA 1999b and 1999c). Potential impacts from new mines can be mitigated by modern control technologies. Older abandoned mines may present complex contamination problems.

Types of mines in relation to hydrologic factors for groundwater impacts include:

1. **Surface open-pit mines in the unsaturated zone, above a confined aquifer, sometimes with a water-filled pit.** A large number of mines in the Colorado Plateau, such as the Yazzie-312 Mine, fall into this category. The Colorado Plateau physiographic province is characterized by low precipitation and high evapotranspiration (Figure 3.5). Much of the Colorado Plateau receives less than 15 inches of precipitation a year. The area's low precipitation and high evapotranspiration reduce the potential for infiltration, although low-frequency, high-intensity rain events may contribute mass movement. Surface mines in New Mexico and Arizona are often isolated from water sources due to lack of dependable surface water or the large vertical distance separating the mines from the confined aquifers below. The U.S. Geological Survey Groundwater Atlas of the United States (Robson and Banta 1995) indicates that the Colorado Plateau has very few surficial aquifers, so water sources are typically derived from deeper groundwater (Figure 3.6). The more numerous surficial aquifers away from the Colorado Plateau pose a greater potential for shallow groundwater contamination outside of the area.
2. **Surface open-pit mines in or just above the saturated zone or close to an aquifer, often with a water-filled pit or pits.** The White King and Lucky Lass mines and the Midnite Mine are examples of this category.
3. **Underground mines in the saturated zone.** Some mines have been developed so deep that radionuclides could move through the aquifer, even in the Colorado Plateau. The Orphan Mine which is located below the rim of the Grand Canyon is a good example of this situation.
4. **Underground mines in an unsaturated zone that may be close to an aquifer.** Mines in the Four Corners area, such as the Lathrop Canyon, are typical of this category. Mines along canyon walls would also be part of this category.

It should be noted that uranium concentrations in undisturbed, near surface groundwater can be quite high, as demonstrated by Sheridan et al. (1962). High evaporation rates as opposed to very low precipitation rates in many parts of the western U.S. may reduce the potential for communication between contaminated surface water and deeper groundwater.

Figure 3.5. Average Annual Precipitation in the Western United States
*Much of the Colorado Plateau receives less than 15 inches (38 cm) of precipitation a year.
The area's low precipitation and high evapotranspiration reduce the potential for infiltration,
although low-frequency, high-intensity rain events may contribute mass movement.*
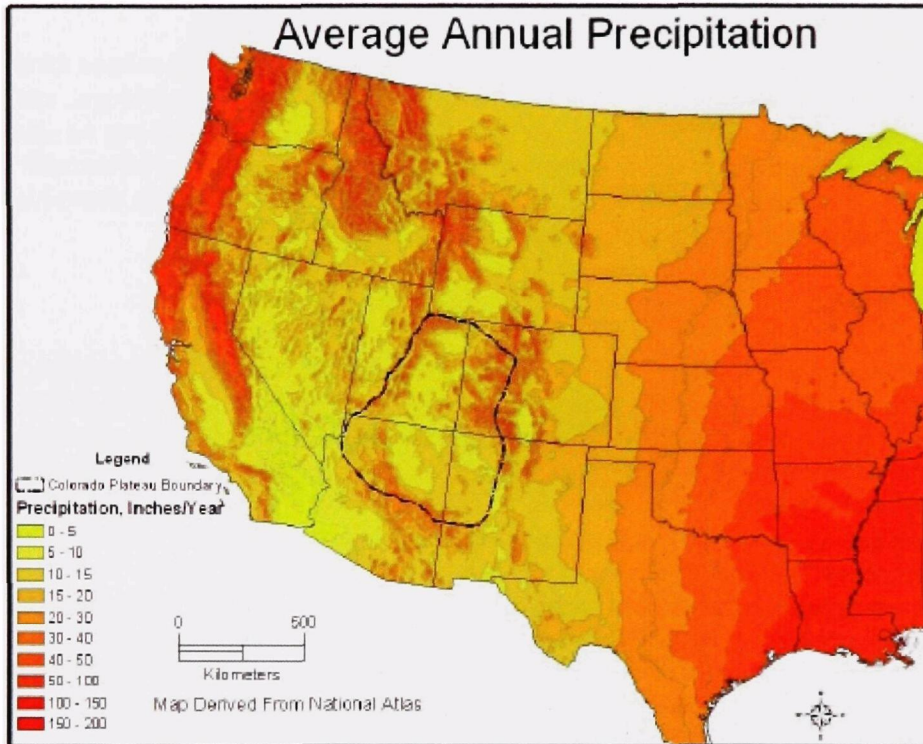
Source: Spatial Climate Analysis Service et al. 2000.

Figure 3.6. Surficial Aquifers of the Colorado Plateau

EXPLANATION

Extent of principal alluvial or eolian deposits

- South Platte River Valley area
- Arkansas River Valley area
- Mountainous area
- Upland plains area
- Basin and Range area
- Rio Grande Basin area
- Roswell Basin area
- — — — Approximate extent of example area discussed in this chapter

SCALE 1:4,000,000
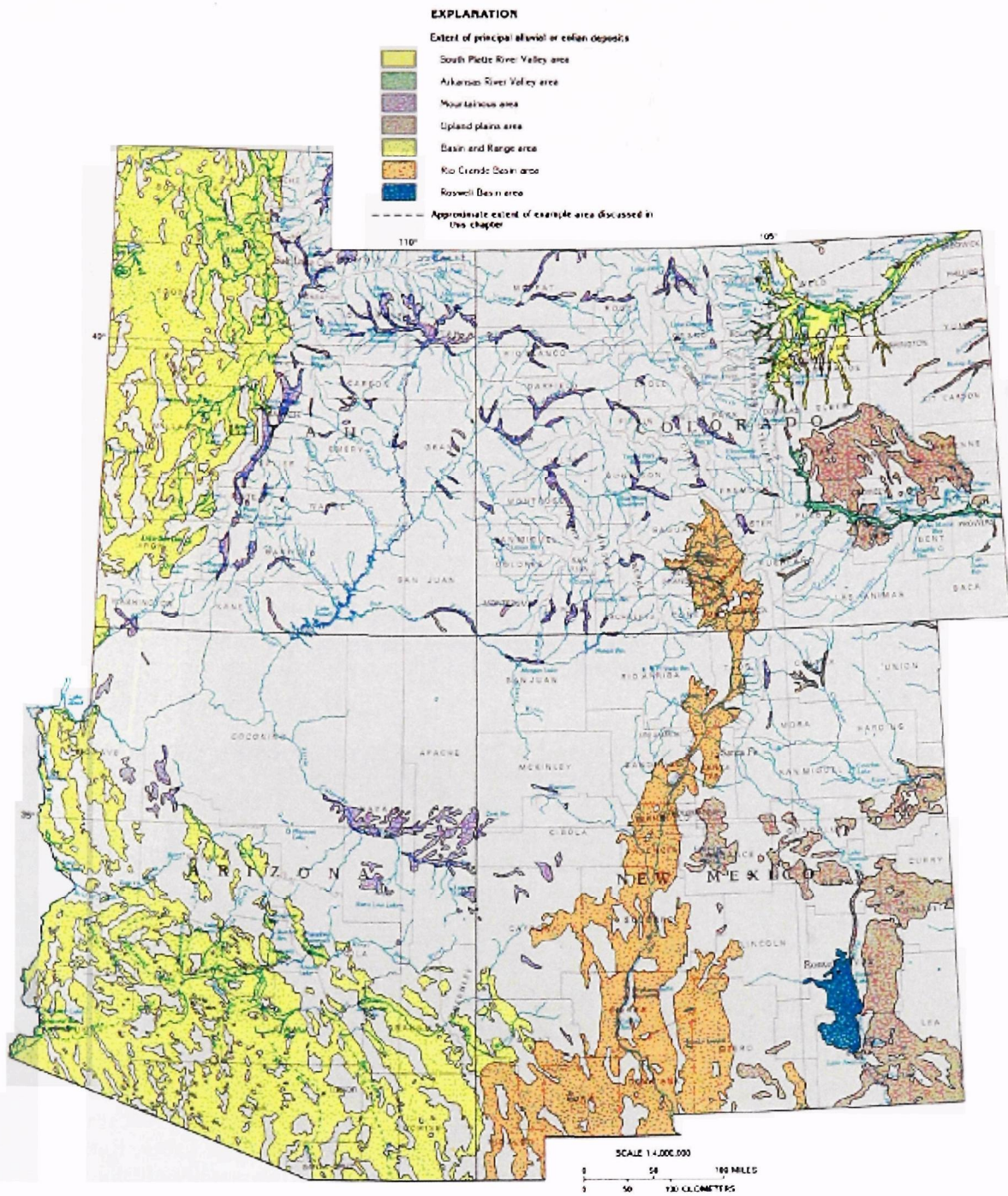
Source: Robson and Banta (1995)

Much of the discussion which follows is from U.S. EPA (1995); however, extensive information on this topic can be found in U.S. EPA (1983b).

Surface water which can enter a mine is generally controlled using engineering techniques. During the life of the mine, mine water from groundwater inflow or seepage is pumped out as necessary to keep the mine dry and allow access to the ore body for extraction. This water may be pumped from sumps within the mine pit or underground workings, or may be withdrawn from the vicinity of mining activity through interceptor wells. Interceptor wells are used to remove groundwater, creating a cone of depression in the water table surrounding the mine; the result is dewatering of the mine. Mine water may be treated and discharged (subject to 40 CFR 440 Subpart C) (see Appendix VI for more information).

The quantity and chemical composition of mine water generated at mines vary by site and are dependent on the geochemistry of the ore body and surrounding area. Prior to being discharged, mine water from uranium mines is usually treated with a flocculent and barium chloride to reduce suspended solids concentrations and to co-precipitate radium. The chemical quality of mine waters may differ from the receiving surface waters. In arid climates, like New Mexico, the discharge of mine water to a receiving stream can completely change the hydrologic conditions of the receiving body. Typically, mine water is discharged to ephemeral streams in arid climates. The mine waters have, in some instances, transformed ephemeral streams to perennial streams. These newly created perennial streams often lose flow to subsurface alluvial material which recharges shallow alluvial aquifers. Studies have documented that infiltration of uranium mine dewatering effluents have been accompanied by a gradual change in the overall chemistry of the groundwater, and the groundwater then bears a greater resemblance to the mine dewatering effluent (U.S. EPA 1995a).

For example, in the Grants Mineral Belt of New Mexico, authorized discharges of mine dewatering effluents have been documented to contain elevated concentrations of gross alpha and beta radiation; radionuclides radium-226 and lead-210; natural uranium; molybdenum; selenium; and dissolved solids, with sulfate in particular (Eadie and Kaufmann 1977). On occasion, arsenic, barium and vanadium are detected (U.S. EPA 1995a).

In cases of abandoned conventional uranium mines, radionuclides, metals, and salts either in solution or as solids may be eroded and carried away from a mine or waste pile and carried by wind and water over time. Waters affected by uranium mining may be on, adjacent to, or at some distance from a mine or mines. Pit lakes, such as the Yazzie-312 (see Appendix III), may be immediately affected by infill from adjacent waste piles and may take on the pollutant burdens of those piles. However, measurements taken by EPA of the Little Colorado River a mile or so downstream from the Yazzie-312 Mine did not demonstrate a correlation with metals and radionuclides that were present in the pit lake, despite erosion channels downslope from the mine leading toward the river.

Similarly, in other case studies (see Appendix III) waterborne erosion from Utah's Canyonlands mines had carried radionuclides and metals only a small distance from the mine mouths. However, surface and subsurface drainage from Arizona's Orphan Mine appeared to be polluting nearby springs. Radionuclides and metals in ground and surface waters from the Midnite Mine in Washington state have spread to areas outside the mined area in surface water and sediments, groundwater, and road dust; most runoff from the mined area flows to three drainages which meet south of the mine and flow into Blue Creek. Runoff and groundwater pollution were also concentrated in groundwater from mines in the vicinity of Blue Water, New Mexico, resulting in a Superfund action to shut a well in.

Geographic and geologic differences play a large role in the likelihood of pollutants naturally migrating from a mine site. The case studies' data, cited in Appendix III, provide information on the metal and radionuclide data from ground and surface waters. Uranium and thorium, and radium to a lesser extent,

can be mobilized by either acidic or alkaline solutions (see section below on Potential for Soil Contamination of Soil). Pyrite and other sulfur-bearing minerals are key determinants as to whether acid mine drainage occurs, while carbonate minerals, organic carbon and carbon dioxide may also influence migration of radionuclides in a neutral or alkaline environment. Geography and climate determine how much water and wind may be present to erode the mine waste and move it away from its place of origin.

Most of the mines located in the sedimentary sandstone deposits of the southwestern United States are not in pyritic formations, and the resulting runoff waters or pit lakes are generally neutral to alkaline in character (pH of seven or higher). Low precipitation rates and the resultant lack of water may further reduce the potential for generation of acid drainage from waste rock, for example, in both the Colorado Plateau and the Shirley Basin of Wyoming.

Runoff waters at Horn Creek below the Orphan Mine had a pH generally between six and eight; Blue Water measurements were generally alkaline in the 8.0 range in wells and river water in the vicinity; Yazzie-312's pit water was measured by Longsworth (1994) at pH 8.7. However, those measurements contrast with the numbers found 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). Acid mine drainage had occurred at Midnite where, for example, in measurements from 1990 to 1992 the pH of water in wells and the pits ranged from 4.0 to 7.2 (Williams and Riley 1993). Acid mine drainage had also occurred at the White King pond, where pH has historically ranged from 3.0 to 4.5 due to acid generation during oxidation of sulfide minerals exposed in the pond bottom, walls, and underground mine workings (U.S. EPA 2001a).

At the end of a mine's active life, pumping typically is stopped and the pit or underground workings are allowed to fill with water. The mine water may be contaminated with radioactive constituents, metals, and suspended and dissolved solids, and reclamation or groundwater protection methods may vary by the responsible land management agency.

It should be noted that groundwater impacted or potentially impacted by mining activities is not necessarily suited for domestic use prior to mining. For example, aquifers containing uranium ores in both Wyoming and New Mexico have been documented as having elevated levels of uranium and other radionuclides prior to the initiation of mining activities (WDEQ 1991; Eadie and Kaufmann 1977).

Uranium is mobile in water, and sediments as discussed in the section below, in both acidic and alkaline conditions (U.S. EPA 1999b and 1999c). Even though the majority of U.S. conventional mines are located in areas of low annual rainfall, the periods of high precipitation (usually Spring and Summer months) may be sufficient to result in eventual migration of radionuclides into groundwater or surface water bodies, soils, and make them available for uptake in vegetation. Radium is considered moderately soluble in natural waters and its fate is controlled mostly by the presence of sulfate and organic materials (U.S. EPA 2004b). The section below on potential for contamination of soil and vegetation is principally drawn from those three reports.

Potential for Soil Contamination

In evaluating the mobility of radionuclides in the environment, an important measure is the element-specific soil/water partition coefficient, which is represented as K_d. In general, the adsorption of uranium by soils and single-mineral phases is low at pH values less than three, increases rapidly with increasing

pH from three to five, reaches a maximum in adsorption in the pH range from five to eight, then decreases with increasing pH at pH values greater than eight. This trend is related to the pH-dependent surface charge properties of the soil minerals and complex aqueous behavior of dissolved uranium (U(VI)). It is especially true near neutral pH, or above (alkaline) conditions where dissolved uranium forms strong molecular complexes with dissolved carbonate. Additionally, soils containing larger percentages of iron oxide minerals and mineral coatings, and/or clay minerals will exhibit higher sorption characteristics than soils dominated by quartz and feldspar minerals. In fact, maximum limits for K_d have been calculated for iron-oxides and clay minerals (Waite et al. 1992).

Radium is an alkaline earth element, and is found naturally only in the +2 oxidation state. In flowing and soil water it can be found dissolved in a pH range of from three to ten. However, in the presence of sulfate bearing waters, precipitation and dissolution of calcium, strontium and barium sulfates may control the concentration of dissolved radium in the soil environment. Only limited K_d are available for radium in soils and sediments. However, it is known to be most strongly absorbed by ion exchange on clay minerals, organic materials, and mineral oxides especially in near neutral and alkaline pH conditions.

Differences in partial pressure of carbon dioxide have a major effect on uranium adsorption at neutral pH conditions. In one study (Ibid.) the percent of uranium (U(VI)) adsorbed on ferrihydrite (an iron oxide mineral) decreases from approximately 97 to 38 percent when carbon dioxide is increased from ambient levels (0.03 percent) to elevated (one percent) partial pressures. Based on this uranium adsorption behavior, the adsorption of uranium decreases rapidly at pH values greater than eight for waters in contact with carbon dioxide or carbonate minerals. This means that in such situations, uranium becomes very mobile and subject to transport in soil and water away from waste sites, potentially for considerable distances (e.g., Kaplan et al. 1994). Extensive literature exists for the fate and transport of radium and the reader is consequently referred to Benes (1990), Frissel and Koster (1990), Dickson (1990), Onishi et al. (1981), Ames and Rai (1978), as well as detailed review in IAEA (1990) and Cothern and Rebers 1990). Much of that is summarized in U.S. EPA (2004b).

Models of contaminant transport typically evaluate the subsurface environment as being divided between a mobile aqueous phase and immobile solid phase (soil). However, under some subsurface conditions, components of the solid phase exist as colloids[4] that may be transported with flowing water in the pore spaces of underground rock and sediment. This may enhance the amount and rate of contaminant transport. Due to field sampling and collection difficulties to enhance available data, contaminant models have mostly ignored this phenomenon. However, subsurface mobile colloids originate from dispersion of surface or subsurface soils, dissolution of natural rock binding cements, and homogeneous precipitation of groundwater constituents (McCarthy and Degueldre 1993). Colloids can be dispersed and become mobile in aquifers due to groundwater chemistry or microbiological changes.

Hazardous Characteristics of Uranium Mine Waste

The primary hazardous characteristics of uranium mine waste are elevated radioactivity as radon emanations and elevated gamma radiation, heavy metals, and contaminated water.

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[4] Colloids are any fine-grained material, sometimes limited to the particle-size range of <0.00024 mm (i.e., smaller than clay size), that can be easily suspended in fluid (Bates and Jackson 1979).

<u>Elevated Radioactivity</u>

Conventional Mines

It should be expected that materials associated with the mining of uranium would have radioactivity above that which would be considered background levels in most parts of the country, not only because uranium is radioactive, but also because the many decay products that accompany it are radioactive as well. The uranium-238 decay chain consists of 13 radioactive elements and the stable end point lead-206 (see Appendix II). Over time, uranium and its decay products achieve a state of equilibrium, meaning that the quantities of each radionuclide are proportional to their half-lives (not considering environmental and geotechnical factors), and their activities are equal. In other words, radioactive equilibrium for a decay chain occurs when the each radionuclide decays at the same rate it is produced. At equilibrium, all radionuclides decay at the same rate (i.e., the same number of atoms disintegrate per unit time for each member of the chain). Understanding the equilibrium for a given decay series helps scientists estimate the amount of radiation that will be present at various stages of the decay.

While high uranium concentrations may be—and often are—measured in wastes, uranium mining TENORM is generally characterized by its more hazardous decay products. In particular, the concentration of radium-226 is a key metric for purposes of classifying waste materials. Radium is the radionuclide of interest at uranium TENORM sites for two reasons: its decay products give off strong gamma radiation that is easy to measure, and it has the most significance for human health risks due to radon generation. Radium is also often used to characterize TENORM, as it can be in serious disequilibrium with uranium in TENORM as a result of processing. Reports of TENORM radionuclide concentrations obtained from wastes at different mine sites can vary greatly, depending on the geographic location, the type of waste sampled, how deep the sampled material was in the waste pile, how long the material had been exposed on the surface, impacts of weather, and many other variables. Following are the results of some sampling efforts which provide a variety of measurements, sometimes conflicting, but nevertheless yielding a range of values for radionuclides found at uranium mine sites.

In one study, radionuclide concentrations in overburden and waste rock were reported from 58 samples collected from 17 uranium mines across the U.S. (U.S. EPA 1985). Data indicate that 69 percent of the samples were elevated in radium-226 concentrations (defined as concentrations greater than or equal to 5 pCi/g (0.185 Bq/g)), and over 50 percent had concentrations above 20 pCi/g (0.74 Bq/g). In another study, the White King mine had radium concentrations of 53 pCi/g (1.96 Bq/g) in the near-surface overburden, while the Lucky Lass mine, mined just a short distance away in a slightly different geologic source rock, had only 2 pCi/g (0.07 Bq/g) in the near-surface overburden (Weston 1997).

The results of another EPA study (SC&A 1989) involving overburden material sampling and analyses indicate average radium-226 concentrations of 25 pCi/g (0.94 Bq/g), ranging from 3 pCi/g (0.113 Bq/g) up to a few hundred pCi/g (> 7.4 Bq/g); the higher concentrations were found in weakly mineralized rock near the ore body. ISL operations for mines other than uranium, can leave behind significant amounts of radionuclides in wastes, though in many cases the aquifer may have been exempted from being considered as a drinking water source, or the aquifer may have been contaminated with radionuclides or metals prior to ISL activities. EPA's 1999 report on TENORM from copper mines in Arizona, for example, provides information on this problem in the copper mining industry (U.S. EPA 1999a).

Additional data, including several more recent studies from mine reclamation assessment studies, 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 (see Appendix V). In fact the State of Wyoming uses 20 pCi/g (0.74 Bq/g) as a key value for mine reclamation because materials with higher measurements are considered unsuitable for placement below the water table, or close to the graded surface according to state reclamation practice (Otton 1998). Protore, on the other hand, was considerably higher in radium-226 activity, with most material in the range of 30–600 pCi/g (1.11–22.2 Bq/g).

Once protore or overburden has been removed from the ground, equilibrium of the radioactive decay chain may no longer be a safe assumption. Data on the parent element and decay product activities of uranium mine overburden have been gathered fairly recently, usually as part of assessment of mine wastes prior to reclamation. Disequilibrium between uranium-238 and its decay products seems common in those waste materials studied in some detail. One observer has noted a tendency for the lower part of waste piles at small mines in southeastern Utah to have higher uranium-238 activities relative to radium-226 activities, suggesting leaching of uranium from the upper part of the piles (Burghardt 1998). In leach studies of mine waste from open-pits in two districts in Arizona and Utah, Longsworth (1994) suggests that uranium is far more soluble in mine waste than radium. In samples of waste material in piles in the Pumpkin Buttes district (AVI 1990), the uranium–radium activity ratio varies from 0.10 to 7.15 (equilibrium would mean the activity ratio equals 1). It is not known whether these disequilibrium conditions are due entirely to weathering of the waste piles, or if disequilibrium conditions also occurred in waste rock and protore surrounding the ore body prior to mining. Other members of the uranium-238 decay chains that are also potentially hazardous may be present in significant quantities due to disequilibrium conditions; lead-214 and bismuth-214 are important surrogates for radium-226 within the radium-226 subchain. Further careful study of equilibrium conditions is warranted.

ISL and Heap Leach Operations

Licensed ISL and heap leach operations, reclamation, and waste disposal are carried out under the regulatory oversight of NRC or its Agreement States. The radionuclide information on these types of uranium extraction facilities is provided for background only, as the wastes are considered to be byproduct materials in accordance with the AEA.

Information on radionuclides present in ISL operation wastewater ponds is very limited. These liquid wastes have some residual uranium and radium-226 activities that range from background levels to concentrations as high as 3,000 pCi/L (111 Bq/L) (Brown 1978). Such liquid wastes are treated with barium chloride to precipitate out radium. The solid wastes are typically comprised of carbonate and sulfate mineral solids that contain several hundred ppm uranium and 300–3,000 pCi/g radium-226 (11.1–111 Bq/g) (Brown 1978). Solid wastes are generally packaged and shipped off site for disposal at licensed facilities.

Not every ISL operation generates large quantities of these wastes, as the quantities are determined by the ore body's geochemical characteristics and its interactions with the leachate solutions. Data collected by EPA in 2000, from reports on files at the NRC and the state agencies in Texas and Wyoming, showed radium-226 in the wastewater can range from background levels to 2,119 pCi/L (78.4 Bq/L), whereas total uranium may be as high as 1,100 mg/L (see Appendix V). NRC and state licensing and permits at uranium solution mining operations sites require cleanup of all surface wastes. Aquifer restoration may or may not be required by the regulating agencies depending upon its geologic and hydrologic conditions. Discussion of regulation of ISL facilities can be found in Appendix VI.

Some low-grade ore, waste rock, and tailings were used in dump or heap leaching, a process that the mining industry considered a form of beneficiation and one that involved spraying ore with acid to leach

out metals (see Chapter 2). When leaching no longer produced economically attractive quantities of valuable metals, and the sites were no longer in use, the spent ore was often left in place or nearby without further treatment (U.S. EPA 1985). Heap leaching generates wastes that are similar to mill tailings in radioactivity. While this mining technique was less often used before the mid-1970s, some abandoned heap leach piles have been reported. After the mid-1970s, mining heap leach piles became subject to state and federal cleanup requirements.

Radon Emanation

Radon (Rn-222) is a key health concern associated with uranium mines and sites where TENORM is found. Radon is part of the uranium decay series, and has the property of being a gas, which means its mobility rate is vastly different from that of radioactive metals. Radon is a decay product of radium-226. When radium is high, radon production is high. The occurrence of radon in underground uranium mines and the occurrence of cancers in Czechoslovakian miners working in such mines formed the basis of one of a number of studies which have established an important epidemiological relationship used for modeling cancer risk from radiation exposures. EPA limits emissions of radon from operating underground uranium mines such that exposures to a member of the public is limited to no more than 10 millirems annually, and the operator must provide a report of their compliance to that requirement to EPA yearly.

Radon measurements in some abandoned 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 at abandoned sites. 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 (7.84 to 19.98 Bq/L) (U.S. BLM 1998). For comparison purposes only (since this in not an operating mine), annual underground uranium mine occupational levels of alpha radiation[5] are limited to no more than four working level months (WLM) at full equilibrium (one WL ≈ 100 pCi/l). A worker's annual exposure to the radon levels reported from the Ross Adams mine would be limited to between 32 and 83 hours.

Radon emanation coefficients (the fraction of radon atoms present in a material that emanate into rock or sediment pore space) for barren (low-activity) sandstone overburden range from three to twelve percent and average about five percent (Barretto 1975). Emanation coefficients 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.

An exhaustive study of emanation for 950 ore samples from all the major sandstone uranium mine districts, deposits at Lakeview, Oregon, and deposits in the Front Range of Colorado (Austin 1978) revealed coefficients ranging from < one percent to 91 percent. The median value for all 950 samples is about 22 percent; however, extreme differences in median values occur regionally. Ores in the Lisbon Valley district of Utah have median values of less than 10 percent, whereas ores in some districts in Wyoming have median values exceeding 50 percent. These data suggest that low-activity sandstone waste material not only has little radon forming in it, but tends to release very little of that radon. However, overburden, waste rock and protore piles with elevated activity not only have much more radon forming,

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[5] Regulated by the Mine Health Safety Administration of the Department of Labor--30 CFR, Part 57, Subpart D.

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 (0.07–2.22 Bq/m^{2}s) for overburden materials to as high as a few hundred pCi/m^{2}s (> 7.4 Bq/m^{2}s) for low-grade ore materials (U.S. EPA 1989b, SC&A 1989). The broad range of radon flux rates is due in part to varying radium concentrations (the parent radionuclide) found in low-grade ores that are at times disposed of with overburden. The average flux rate, based on data from 25 mines, was estimated to be 11.1 pCi/m^{2}s (0.41 Bq/m^{2}s) for overburden materials. A radon flux rate of 92.4 pCi/m^{2}s (3.42 Bq/m^{2}s) was reported for a spoil area located at the Day Loma mine in the Gas Hills District of Wyoming (SMI 1996); however, this material appears to have been a heap leach pile. For comparison, background radon flux rates from soils are known to vary from about 0.6 to 5.0 pCi/m^{2}s (0.02 to 0.19 Bq/m^{2}s) (SC&A 1989; U.S. NRC 1980). However, Kennecott Uranium Company (2004) found an undisturbed area adjacent to a uranium extraction operation which had background radon flux rates in excess of 100 pCi/m^2-sec; in addition, the company believes other undisturbed uraniferous outcrops in the Gas Hills of Wyoming should also have elevated radon flux rates.

In its 1983 report to Congress, EPA cited measurement results for various waste materials taken at six mines (Table 3.9). The data indicated an average radon flux estimate of 9.4 ± 3.9 pCi/m^{2}s (0.35 ± 0.14 Bq/m^{2}s). The report assumed that an average radon flux rate of 8.7 pCi/m^{2}s (0.32 Bq/m^{2}s) existed for overburden materials. In light of the 25 mine study results from the 1989 review, a radon flux rate of 10 pCi/m^{2}s (0.37 Bq/m^{2}s) is assumed to be representative, while recognizing that in some instances radon flux rates could be higher by a factor of six.

Table 3.9. Radon Flux from Selected Uranium Mine Wastes

Flux rates of radon from six selected uranium mine wastes vary by a factor of up to four.

Type of Mine	Waste/Material	Average Radon Flux pCi/m^{2}s (Bq/m^{2}s)
Underground		
San Mateo	Waste pile	18 (0.67)
Barbara J#1	Waste pile	7.9 (0.29)
Surface		
Poison Canyon-1	Protore Overburden pile	7.0 (0.26) 6.7 (0.22)
Poison Canyon-2	Protore Overburden pile	5.3 (0.2) 9.8 (0.36)
Poison Canyon-3	Protore Protore	11 (0.4) 24 (0.89)
Morton Ranch	Overburden	9.7 (0.36)

Source: U.S. EPA 1983b. (Table modified to substitute the term Protore for "Subore")

Given that the current overburden stockpiles represent decades of mining activities, the radon flux reported in various field studies may in fact reflect the aggregate properties of materials accumulated at one location and not that of the surface material. Because most overburden piles also contain some amounts of weakly mineralized waste rock, the results are likely to be influenced by the presence of materials containing higher levels of uranium. However, large volumes of this weakly mineralized waste are not expected. Since the amount of overburden far exceeds the volume of this waste, it is assumed that

radon emanation rates from such material would not significantly increase the overall average emanation rate.

Elevated Gamma Radiation Exposure Rates

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 ranged from 10 to 85 μR/hr, averaging about 20 μR/hr.

Gamma radiation exposure measurements were taken on overburden piles in support of the characterization of 25 uranium mine sites located in five states (U.S. EPA 1989b, SC&A 1989). Additional information also comes from abandoned mine reclamation assessment studies from 1988 to 1996 and is included in Appendix V. In these various studies, exposure rates for overburden materials range from 20 μR/hr to 300 μR/hr, with an average value estimated at 50 μR/hr, including background. Protore ranges from 80 to 1,250 μR/hr, with an average value estimated at 350 μR/hr. These average values may be significantly higher for waste materials at the surface of underground mine sites because of the greater proportion of stockpiled protore to waste. Exposure levels of 200 to 1,000 μR/hr would appear to correspond to about 0.1 to 0.3 percent uranium ore grade.

Heavy Metals in Mine Wastes

A number of heavy (i.e., hazardous) 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. Available measurement data have tended to focus on individual sites rather than survey many mines in an area. To that extent, some of the examples in Tables 3.9–3.11 provide a snapshot of what is known about the occurrence of metals in these wastes. The reader is referred to U.S. EPA (1983b) which discusses in depth the movement of metals and radionuclides through air, water, and groundwater, including leaching and other chemical reactions that move contaminants from mine sites to the surrounding environment.

Table 3.10 from Wogman (1979) shows the analytical results of metals analysis from grab samples taken at two mines, one in Wyoming and the other in New Mexico; except for selenium, vanadium and arsenic, there did not appear to be a relationship between uranium mining materials and stable metals present in the overburden. Table 3.11 provides the results of sampling and analyses of overburden and protore piles at the Yazzie-312 Mine in Arizona (Panacea 2002); uranium and thorium concentrations as well as some heavy metals in protore samples were much higher than those taken from overburden, and iron and arsenic exceeded EPA Region IX preliminary soil remediation cleanup goals for industrial contaminated sites. Table 3.12 shows the results of metals analyses for waste piles associated with several small underground mines in a complex at Canyonlands National Park in Utah (Burghardt et al. 2000); there, even though some of the metal levels may be high, contamination had not spread far from the waste piles.

Table 3.10. Metals Sampling Data from Uranium Mines in New Mexico and Wyoming

This table reproduces information taken from mines in New Mexico and Wyoming on heavy metals present in conventional mine wastes. Concentrations of metals are in µg (micrograms) per gram of soil.

Samples	Concentration (µg/g)														
	As	Ba	Cu	Cr	Fe[a]	Hg	K[a]	Mn	Mo	Pb	Se	Sr	V	Zn	U
Wyoming															
1. Top Soil Piles	3.2	700	13	46	1.3	<4	2.2	190	2.9	23	<1	89	60	37	6
2. Protore	<1.8	6800	9	<36	1.2	10	2.3	140	<2.2	22	2.1	128	<100	25	61
3. Ore	5.4	800	9	<27	1.1	<7	2.3	180	<2.9	16	28	94	200	25	370
New Mexico															
4. Background Soil	4.1	450	12	<23	0.9	<4	1.8	200	5.5	12	<1	72	<60	22	<5
5. Background Soil	2.3	440	9	<20	0.8	<4	1.6	190	4.9	13	<1	50	<50	19	<5
6. Waste Pile	7.8	540	11	<28	0.8	<5	1.4	260	2.5	10	<1	99	<70	23	8
7. Waste Pile	14	280	21	<43	0.7	<8	0.5	750	<2.8	31	3.1	178	180	23	189
8. Protore + Waste	4.1	45	22	<51	0.3	<6	0.1	446	<1.8	25	<1.4	179	<55	13	57
9. Ore	6.0	64	27	<48	0.4	<6	0.2	673	<1.8	31	1.5	323	<55	14	......

Note: As = Arsenic, Ba = Barium, Cu = Copper, Cr = Chromium, Fe = Iron, Hg = Mercury, K = Potassium, Mn = Manganese, Mo = Molybdenum, Pb = Lead, Se = Selenium, Sr = Strontium, V = Vanadium, Zn = Zinc, U = Uranium.

(a) Units are percent.

Source: Wogman (1979)

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Table 3.11. Radionuclides and Metals from Protore and Overburden, Yazzie-312 Mine, Arizona

This table provides a summary of data analyses from six protore and overburden waste piles at the Yazzie-312 Mine prior to reclamation. Twelve samples were analyzed for uranium and thorium radionuclides content and other radiological properties, as well as content of 23 metals. Selected data shown below are the range of average and total uranium, and thorium, as well as seven selected heavy metals for one protore (WP-6), one overburden (WP-3) pile. Additionally, values from all six waste piles are also provided, For reference, the EPA, Region IX preliminary remediation goal (PRG) for contaminated industrial sites is also shown.

Sample Range	Total Uranium pCi/g	Total Thorium pCi/g	Arsenic mg/Kg	Iron mg/Kg	Lead mg/Kg	Mercury mg/Kg	Selenium mg/Kg	Thallium mg/Kg	Vanadium mg/Kg
Waste Pile 6 –Protore range of measurements	61.8-- 121.9	36.8— 63.4	1.1—9.7	6000-- 8100	21.3— 48.3	0.05— 0.19	0.13— 0.32	0.84— 18.4	12.3—20.5
(Avg. 3 samples)	(90.2)	(36.8)	(4.2)	(7207)	(39.1)	(0.13)	(0.25)	(6.73)	(17.7)
Waste Pile 3-Overburden range of measurements	2.4—3.6	3.0—4.85	1.3—1.9	1020-- 1430	11.8— 13.8	0.01— 0.01	0.27— 0.93	0.24— 0.28	15.2—33.5
(Avg. 3 samples)	(2.9)	(3.9)	(1.5)	(1356)	(12.6)	(0.01)	(0.50)	(0.26)	(21.4)
All Protore and Overburden Samples Range of measurements	2.4— 121.9	3.0—63.4	0.7—17	6000-- 16200	7.9— 48.3	0.00— 0.19	0.13— 0.95	0.19— 18.4	8.2—33.5
(Avg. 12 samples)	(32.7)	(15.5)	(4.6)	(9867)	(21.8)	(0.05)	(0.47)	(1.91)	(17.0)
Metals Preliminary Remediation Goal			1.6	10000	800	310	5100	67	1000

Source of Data: Panacea (2002), U.S. EPA (2004)

Table 3.12. Metals in Canyonlands National Park Mine Waste Piles

Comparison of concentrations of four toxic metals from Canyonlands National Park spoil piles from 12 underground mines. Multiple sampling locations were picked for each mine's waste site. Samples were taken at multiple depths for each waste site and mixed together (composited). The results provide the range of values for all samples, and for a few specific mines. The statistical analysis of two standard deviations provides a measure of the spread of values for the samples taken. All samples are reported in mg/Kg.

Analyte	Sample Range All Samples mg/Kg dry weight	Mine 4 Avg ± 2 SD	Mines 5, 6, 7 Avg ± 2 SD	Mine 12 Avg ± 2 SD
Arsenic	19.1–155.1	50.7±5.7	124±13.3	12.1±1.9
Copper	79.3–7,910	429±79	3,500±982	322±25.7
Manganese	214.5–1,410	850±34	948±119	702±59.3
Selenium	0.3–2.4	0.7±0.03	2.7±0.8	0.3±0.02
Vanadium	4.8–35.6	8.1±0.8	9.8±1.3	29.6±2.5

Note: 2 SD = two standard deviations.
Source: Burghardt et al., 2000

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. Analyses conducted on water samples downstream from the Canyonlands mines found a correlation (similar concentration levels above background levels) between manganese and selenium, though this dropped off rapidly within 150 feet (46 meters) of the mines.

However, in the Yazzie-312 Mine example from Table 3.11, water from rain events over 40 years carried sediment in overburden and protore piles back into the pit (then a lake) from which they were originally derived. Metal concentrations found in samples of spoil pile sediments and sediments collected from the bottom of the pit lake were both elevated to the same general degree (order of magnitude concentration).

Uranium Mill Tailings

The following material summarizes only a small portion of information provided in U.S. EPA (1995; 1989b; 1986;1983 a,b,c,d; and 1982), and NRC (1980) and the reader is referred to those reports for much more detailed information on uranium milling and mill tailings. As mill tailings are considered byproduct materials under the AEA and not TENORM, this section is provided only in order to provide a more complete background and understanding of the uranium production industry.

Operational mills function independently of specific mines and generate materials that are, in most cases, unique from those generated at the site of extraction. Under UMTRCA (Uranium Mill Tailings Radiation Control Act; see Appendix VI for more information), source handling licenses place specific requirements on the disposal of radioactive wastes; the design and construction of tailings impoundments address NRC or its Agreement State requirements for permanent storage of these wastes. Radionuclide-containing wastes generated by ISL operations are typically shipped to tailings impoundments at mill sites.

The principal waste generated by conventional beneficiation operations are tailings. ISL operations, and to a more limited extent conventional mills, generate waste leaching solutions. Disposal of these wastes is

dependent on the type of operation; beneficiation wastes generated by ISL are disposed of by different methods, but most often shipment to NRC-licensed waste disposal facilities. Most beneficiation wastes generated at conventional mills are disposed of in tailings impoundments.

Waste constituents of concern include radionuclides (radium, radon, thorium, and to a lesser extent lead), arsenic, copper, selenium, vanadium, molybdenum, other heavy metals, and dissolved solids. Brines, spent ion exchange resins, and chemicals used in beneficiation operations are also constituents of wastes generated during beneficiation.

Most wastes generated by conventional mills are disposed of in tailings impoundments. Wastes are primarily disposed of in the form of a slurry composed of tailings, gangue[6] (including dissolved base metals), spent beneficiation solutions, and process water bearing carbonate complexes (alkaline leaching) and sulfuric acid (acid leaching), sodium, manganese, and iron. The characteristics of this waste vary greatly, depending on the ore, the beneficiation procedure, and the source of the water (fresh or recycled). The liquid component is usually decanted and recirculated to the crushing/grinding or leaching circuit.

Tailings typically consist of two fractions, sands and slimes. The sand and slimes may be combined and deposited directly in the impoundment or may be distributed through a cyclone such that the sand fraction is directed toward the dam while the slimes are directed to the interior of the pond (Merritt 1971).

The fate of radionuclides is of special interest in uranium mill tailings. Radium-226 and thorium-230 are the principal constituents of concern and are associated with the slime fraction of the tailings. Radon-222 (gas) is also a tailings constituent. The concentrations of radionuclides in the tails will vary depending on the leach method used (thorium is more soluble in acid than alkaline leaches). Typically, tailings will contain between 50 and 86 percent of the original radioactivity of the ores depending on the proportion of radon lost during the operation (Merritt 1971). Other tailings constituents (including metals, sulfates, carbonates, nitrates, and organic solvents) would also be present in the tailings impoundment depending on the type of ore, beneficiation methods, and waste management techniques. Table 3.13 below provides an overview of typical characteristics of uranium mill tailings.

ISL wastewater bleed solutions and lixiviant leaching solutions constitute the major source of wastes directed to lined evaporation ponds at ISL facilities. These solutions consist of barren lixiviant and usually have elevated levels of radium; other contaminants (metals, salts) are limited to what may have been dissolved by the lixiviant or contaminants in solutions used for beneficiation. Barium chloride is added to the evaporation ponds which, in the presence of radium, forms a barium-radium-sulfate precipitate. This precipitate forms the majority of the sludges in the settling/evaporation ponds at ISL operations. Alkali chlorides and carbonates are other likely constituents (U.S. EPA 1983b). These sludges are collected at the completion of mining (unless required sooner) and disposed of at an NRC-licensed disposal facility. Information regarding the radionuclide levels of the evaporation ponds can be found in Appendix V.

ISL operations typically store spent ion exchange resins with waste in labeled containers prior to disposal at an NRC-licensed disposal facility. Conventional mills would typically dispose of spent ion exchange resins in the tailings impoundment. Reverse osmosis brines, acid/alkaline leaching, solvent extraction, stripping and precipitation wastes and materials also are disposed in tailings impoundments.

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[6] Gangue is defined as the valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration.

Table 3.13. Typical Characteristics of Uranium Mill Tailings

Particle sizes, chemical compositions, and radioactivity levels are presented in this table[a]:
Individual mill impoundment materials can and will vary dependent on ores
and mining or extraction processes used.

Tailings component	Particle size (μm)	Chemical composition	Radioactivity characteristics
Sands	75 to 500	SiO_2 with <1 wt % complex silicates of Al, Fe, Mg, Ca, Na, K, Se, Mn, Ni, Mo, Zn, U, and V; also metallic oxides	0.004 to 0.01 wt % U_3O_8[b] Acid leaching:[c] 26 to 100 pCi ^{226}Ra/g; 70 to 600 pCi ^{230}Th/g
Slimes	45 to 75	Small amounts of SiO_2, but mostly very complex clay-like silicates of Na, Ca, Mn, Mg, Al, and Fe; also metallic oxides	U_3O_8 and ^{226}Ra are almost twice the concentration present in the sands Acid leaching:[c] 150 to 400 pCi ^{226}Ra/g; 70 to 600 pCi ^{230}Th/g
Liquids	d	Acid leaching: pH 1.2 to 2.0; Na^+, NH_4^+, $SO_4^{\,2}$, Cl^-, and $PO_4^{\,3}$; dissolved solids up to 1 wt % Alkaline leaching: pH 10 to 10.5; $CO_3^{\,2}$ and HCO_3^-; dissolved solids 10 wt %	Acid leaching: 0.001 to 0.01% U; 20 to 7,500 pCi ^{226}Ra/L; 2,000 to 22,000 pCi; ^{230}Th/L Alkaline leaching: 200 pCi ^{226}Ra/L; essentially no ^{230}Th (insoluble)

Source: U.S. DOE (1997)

[a] *Adapted from information in NRC (1980).*

[b] *U_3O_8 content is higher for acid leaching than for alkaline leaching.*

[c] *Separate analyses of sands and slimes from the alkaline leaching process are not available. However, total ^{226}Ra and ^{230}Th contents of up to 600 pCi/g (of each) have been reported for the combined sands and slimes.*

[d] *Particle size does not apply. Up to 70 vol % of the liquid may be recycled. Recycle potential is greater in the alkaline process.*

In addition to Table 3.13, there are many available analyses on uranium mill tailings which have been placed in impoundments. The reader is referred to the EPA and NRC reports mentioned at the beginning of this section for descriptions of individual sites. As a recent example, however, the Department of Energy conducted an environmental evaluation of the former Atlas Uranium Mill near Moab, Utah (U.S. DOE 2005). In that study, they characterized the mill tailings in the impoundment and vicinity properties as containing about 12 million tons of contaminated materials, of which approximately 10.5 million tons were tailings. The mean radium-226, ammonia, and uranium concentrations for the tailings were 516 pCi/g, 423 milligrams per kilogram (mg/kg), and 84 mg/kg, respectively. Other constituents, including iron, manganese, copper, lead, molybdenum, and vanadium, were present in lesser amounts. The pH values of the tailings were near neutral but had zones of pH values as low as 2.5 and as high as 10. With respect to grain size of tailings, approximately half of the material was classified as slimes.

One matter which has affected some mill operations, and consequently the waste in the impoundments, is that the NRC has the authority to amend a uranium mill license to allow for disposal of source material termed "alternative feed". This material, derived from a mining or other operation other than a uranium mine or uranium ISL operation, contains source material and the mill owner is agreeable to processing it at the mill to extract uranium. Guidance for amending the license to allow for processing this alternate feed was issued by NRC (2000a).

Radium-226, thorium-230, and radon-222 (gas), and their decay products are the radionuclides present in uranium mill tailings that are of principal concern to human health and the environment. Under UMTRCA, EPA has the responsibility to establish standards for exposure of the public to radioactive materials originating from mill tailings and for cleanup and control standards for inactive uranium tailings sites and associated vicinity areas. EPA's regulations in 40 CFR 192 apply to remediation of such properties and address emissions of radon, as well as radionuclides, metals, and other contaminants into surface and groundwater. Under provisions of the Clean Air Act, operators of uranium mills must comply with EPA's radon emission requirements in 40 CFR 61, Part W, including providing an annual report to the Agency on their adherence to the regulations. The NRC or its Agreement States license uranium mills. Under statutory requirements of the AEA and UMTRCA, NRC has issued regulations in 10 CFR Part 51 to provide for environmental protection for domestic licensing and related regulatory functions, while those in 10 CFR Part 20 cover radiation protection from hazards of mills and their wastes, and 10 CFR Part 40 cover uranium source licensing provisions. NUREG 1620 (U.S. NRC 2004) provides guidance for the approval of reclamation plans of active uranium mills (reclamation of uranium mill tailings impoundments is covered in Chapter 4 of this report).

As part of those requirements, tailings piles must have a cover designed to control radiological hazards for a minimum of 200 years and for 1,000 years to the greatest extent reasonably achievable. It must also limit radon (Rn-222) releases to 20 pCi/m^2/s averaged over the disposal area. Radon release limitation requirements apply to any portion of the tailings disposal sites unless radium concentrations do not exceed five pCi/g in the first 15 cm below the surface, and 15 pCi/g in layers more than 15 cm below the surface.

Chapter 4. Uranium Mine and Extraction Facility Reclamation

This chapter is not intended to serve as guidance, or to supplement EPA or other agency environmental requirements. Instead, it is an outline of practices which may or have been used for uranium site restoration.

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.

When a uranium mine, mill, or other uranium extraction facility has exceeded regulatory requirements for radiation control, or has had an unauthorized release of metals or other contaminants, the cleanup or other methods used to remove or contain the contamination is termed remediation. Remediation of a source of contamination may be a short-term response or an interim step in the long-term reclamation of the site

Site reuse is a significant issue for radiation sites. The extent to which a uranium mine site can be reused for other purposes where humans may spend periods of time for work, recreation, or even residential purposes is highly dependent on the extent of cleanup and removal of the potential for radiation exposure. Therefore, the end state of reclaimed uranium sites and the techniques used to achieve the end state, will vary on a site-by-site basis, and dependent upon the regulatory agencies involved. However, most of what is described in this chapter is process oriented, rather than regulatory in nature, and much of it is derived from the Nuclear Energy Agency's (NEA) and IAEA's joint publication *Environmental Remediation of Uranium Production Facilities* (NEA/IAEA/OECD 2002) rather than any single set of federal (including EPA) or state requirements. Appendix VI provides information on federal and state agency regulatory requirements for reclamation and remediation of these facilities.

A number of handbooks and guides provide much more detailed information on mine site reclamation, including *The Handbook of Western Reclamation Techniques* (Ferris et al. 1996), *Handbook of Technologies for Avoidance and Remediation of Acid Mine Drainage* (Skousen et al. 1998), *Abandoned Mine Site Characterization and Cleanup Handbook* (U.S. EPA 2000d), *EPA's National Hardrock Mining Framework* (U.S. EPA 1997b), and *Environmental Handbook: Effects of Mining on the Environment and American Environmental Controls on Mining* (Marcus 1997).

While this chapter does include some discussion of reclamation techniques applicable to uranium extraction facilities as background information, reclamation of uranium extraction facilities are governed by the NRC's regulations. Readers interested in finding out more on this topic should consult NRC guidance documents such as *Standard Review Plan for the Review of a Reclamation Plan for Mill Tailings Sites Under Title II of the Uranium Mill Tailings Radiation Control Act of 1978* (U.S. NRC

2004), *Standard Review Plan for In Situ Leach Uranium Extraction License Applications* (U.S. NRC 2003), *Design of Erosion Protection for Long-term Stabilization* (U.S. NRC 2002), *and NMSS Decommissioning Standard Review Plan* (U.S. NRC 2000b).

Although most conventional uranium mine sites in the U.S. are in rural areas remote from population centers, many have also been located in close proximity to or within communities, such as parts of the Navajo Reservation in New Mexico, or may be accessible to recreational visitors on federal lands (see Volume II of this report, U.S. EPA 2006a), and a few have been subject to Superfund cleanups. Thus, in some instances, uranium mine sites can result in environmental impacts, which may include potential public exposure to radon and radiation; contamination of groundwater and surface water supplies (via acid drainage and the mobilization of heavy metals); natural habitat disturbance; increased instability of the land such as erosion and slope stability failure; and the remaining physical safety hazards. Left exposed to the environment, these sites could pose hazards to the local community and biota, and the radioactive wastes could be subject to potential misuse as building materials.

This chapter attempts to cover available uranium reclamation techniques and to summarize some processes for remediating a uranium mine or extraction facility. The discussion that follows breaks the reclamation process into two forms of uranium mining and extraction wastes: the waste products from open-pit or underground mines (which may include TENORM for which EPA, federal land management agencies, Tribes, and states have jurisdiction) and the waste products from ISL, heap leaching, and milling (which are regulated by the NRC or its Agreement States) as byproduct material. Several types of wastes generated need reclamation, and the wide disparity in waste management practices over the years has resulted in diverse conditions at various mining and extraction sites.

Uranium mining and extraction facilities being reclaimed now are mostly those that have current owners, which are primarily ISL operations (under license to the NRC or its Agreement States); conventional mines that were either closed or in suspension with a current or successor owner; or abandoned mines with or without a current or successor owner. In many cases, federal, state, Tribal, or local government agencies are involved in managing or requiring the reclamation process to begin.

Characterizing a Mining Site

Site characterization is the first step required in the remediation and reclamation of former uranium mining facilities. Data on site properties and conditions form the basis for current environmental assessments, risk analyses, decommissioning plans, reclamation programs, monitoring programs, and final public use of the site. Data quality objectives and quality assurance and quality control (QA/QC) procedures may or may not be in place before the data are collected. Mine age, management, and regulatory practices in place during the operation of each mine, especially some older unreclaimed mines, may vary significantly. Thus, the requirements for QA/QC issues can also vary significantly, depending on requirements of the regulatory agencies involved.

The surface and mineral ownership of a site will play an important part in site reclamation and remediation. The land status will partially determine the regulatory regime. Whether the site is on Tribal, federal, state, acquired or private lands, or a combination (split estate) will affect many actions. Ownership or stewardship will also be an important factor in financing reclamation and/or remediation. This will also identify the regulatory regime and the possibility of developing partnerships to resolve conflicts and ensure all stakeholders are involved. Identifying current land uses will also drive decisions.

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, a plain, 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.

Climatological and hydrological characterization includes annual and monthly precipitation, annual and monthly temperature patterns, annual and monthly wind speed and storm patterns, distribution of surface water bodies, and data on evapotranspiration rates. Hydrological and hydrogeochemical characterization includes identification of aquifers, impermeable strata and depths to water tables, groundwater contours, hydraulic gradients and flow rates, ground and surface water quality, and changes in surface- and groundwater characteristics over time.

Understanding a site's ecology is also important to its characterization. Understanding the flora in the area is important in revegetating the site, and understanding the fauna in the area and their seasonal habits is important in developing a reclamation plan that will have minimal impact on the ecology.

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, and radiological characteristics determine how much reclamation must be conducted.

As mentioned above, having data on radiological background conditions is very important in the development and design of any remediation and reclamation plan. The average natural background dose in the United States is about 300 mrem/year, much of that originating from naturally occurring radionuclides that include uranium and thorium isotopes. Sites selected for uranium mining will generally have higher levels of natural background. Radiation surveys for establishing background can help determine statistically appropriate reference levels of natural soil background in areas uncontaminated by human activity. This information can aid in establishing the extent of any additive man made contamination, determining site related impacts, and assessing remediation goals at or above background radiation levels (U.S. EPA et al. 2001; Eisenbud and Gesell 1997; NCRP 1987b).

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, for example the creation of an ore transport station for ore produced by several mines in a common area. 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. Computer modeling of collected data, and calculations of potential transport pathways may guide more detailed sampling and surveys to characterize and identify how far and in what directions radionuclides, metals, or other contaminants have moved or been taken away from the mine site. Examples of two recent reconnaissance radiation surveys conducted by EPA in areas off site of uranium mines include U.S. EPA and USACE (2000) on the Navajo Reservation, and Dempsey et al. (1999) on the Spokane Indian Reservation.

When releases of contaminants have occurred off site of uranium mines, they may be subject to remediation actions of federal, Tribal, or state governments in accordance with their statutory and regulatory authority (see Appendix VI). In the case of the Spokane Indian Reservation in Washington state, a radiation survey conducted by EPA identified where uranium ore and related materials had spilled out of trucks driving off site from the Midnite Mine to the Dawn Mill. The mining company agreed to remove the spilled ore and remediate the sites. The work was completed in March 2005.

Sometimes, it is possible to locate original pre-mining exploration survey radiation data, which can help in establishing background levels. Surveying techniques for performing radiological characterization include direct measurement and scanning with radiation survey instruments, and site sampling followed by lab analysis. Direct measurement and scanning are best suited for determining total surface activities. However, these measurements in some cases cannot be used for accurately determining reclamation or remediation goals. In these cases, sampling followed by lab analysis may be best suited for characterization, but extensive sampling can become very expensive. Protocols and procedures for final site surveys are detailed in the *Multi-Agency Radiation Survey and Site Investigation Manual(MARSSIM)* (U.S. EPA et al. 2001). An important issue in a radiation site survey and particularly for abandoned conventional mines, and discussed in the MARSSIM, is determining what constitutes background levels of radiation to ascertain what changes may have occurred at the site due to human activity, and attempting to distinguish the changes from natural background radiation.

In those instances where mines are located near populated areas, socioeconomic characteristics can influence methods and clean up goals for mine reclamation. Final land use generally takes into account future human and environmental exposures from the reclaimed site.

The Reclamation Process

TENORM bearing overburden, waste rock and other materials at sites of former uranium mines that are not in compliance with applicable criteria and standards may need remediation depending on requirements of regulating and land use management agencies. The objectives of remediation, dependent on the federal, state, Tribal or even local requirements, may include removing potentially harmful effects on the environment and human health, to render impoundments stable over prolonged periods of time, and ensure that the sites are established with natural self-sustaining vegetation if possible. In addition to characterizing sites, the following information is generally gathered to develop the final plan for remediation and public use of the land: agreed final land use; physical characteristics, such as tonnage and area of rock piles; maximum area that can be used for final disposal and maximum height for contouring; maximum permitted slope angles; erosion characteristics for proposed combinations of waste rock and possible limitations on use of erosion control structures of final capping; availability, quantity, and quality of soil for use in revegetation; and experience with revegetation of similar rock types in the region.

Overburden and Waste Rock Reclamation

Overburden and waste rock from mining operations are usually placed above ground in piles. An important decision that is usually made first for reclamation is whether the waste can be placed back into the mine excavation, either an open-pit mine, or underground mine. Often this decision will depend on the presence of water at the site, and whether leaching of contaminants and radionuclides from waste placed back in the excavation is likely to occur. In many instances, the mine may have partially collapsed, making it impossible to return all wastes to the original workings, which would then require different reclamation or disposal methods for the remaining materials. In some cases, such as the Lathrop Canyon mines in Canyonlands National Park, Utah (see Appendix III), a decision was made by the National Park Service not to reclaim the abandoned mines but just bar the mine opening with wire, and post radiation signs to keep members of the public out of the workings. This decision was made due to the remoteness of the mine site, low visitation rate, and anticipated low risk to the public and environment from radiation at the site (Burghardt et al. 2000). In other sites, land management agencies have returned waste rock to the underground mine, then placed barriers at the mine portal which allow bats to enter and leave freely for roosting.

In those cases where mine waste piles have either been returned to an original open-pit excavation, or left in place, reclamation has generally been implemented by installation of a dry-cover system. The first step in constructing a dry-cover for overburden and waste rock piles is to recontour the above-ground materials. This action improves both the long-term stability of the vegetative cover and landscape integration. In doing so, steps are usually taken to ensure that all settling has occurred prior to re-contouring, to prevent depressions on the surface that allow water to collect and ultimately infiltrate the waste pile, and to mediate unsuitable slope angles that promote erosion. There are always exceptions. In semiarid environments, leaving some engineered rills, depressions, or berms has aided in creating micro-environments and holding water, on a small scale, for revegetation (Leshendok 2004).

A suitable site usually is designed to last far into the future, though regulatory controls for most mines end once the facility has been closed. Closure designs may recognize that the radionuclide hazards may exist on the order of hundreds to thousands to millions of years, due to the long half-life of the radionuclides involved, and incorporate the impacts of weathering to prevent spreading of radiation. Designs commonly are based on human and societal abilities to maintain regulatory controls and not on the period of the hazard's existence. Capping materials are not usually a source of additional pollution and are generally compatible with the agreed final land use. Water management techniques commonly are designed to divert surface water away from the impoundment, treat surface precipitation on the impoundment for suspended solids only, and treat water draining from underground mine areas for extended periods of time.

The last steps for reclamation generally are revegetation and maintenance. Revegetation improves the long-term stability of the reclaimed land to integrate with surrounding undisturbed land, strengthens resistance to erosion, and limits net infiltration of precipitation by enhancing evapotranspiration. While revegetation can be allowed to develop naturally, one technique is hydro-seeding, which spreads suspended seeds in nutrient solutions with added organic gels. This may achieve good results in the presence of some soil; though its use in many areas with only rock, or extreme aridity, has been unsuccessful. In cases where the topsoil generates acid, special treatment with lime may be necessary. The use of sewage treatment plant biosolids as a growth medium has been tried successfully on other types of mines and could be used for uranium mines as well.

While passive controls are usually preferable, maintenance may be required to cope with surface disturbance during the first few years, such as local erosion and settling. Maintenance efforts may include surveying the integrity of the surface cover and intervening to repair detected damage to vegetation.

Heap-Leaching Reclamation

The heap-leaching process is not currently in use by the U.S. uranium industry, but has been used in the past. Wastes derived from this method, regulated as byproduct material by NRC or its Agreement States, form piles that if not sent to uranium mill tailings impoundments for disposal, would need to be reshaped for proper integration into the landscape for reclamation. Many heap-leaching piles were accompanied by drainage systems that could be preserved for remediation purposes. In some select cases, the heap-leaching pile would be flushed to further remove all uranium and other valuable substances prior to considering the pile as waste. Once the pile is considered waste, the reclamation technique for heap-leaching waste has been contouring for stabilization, and capping. Capping further reduces leaching by reducing water infiltration rates, preventing the dispersion of radioactive material by water and wind erosion, decreasing radon emanation rates, and reducing direct exposure to gamma emissions. Under NRC and Agreement State controls, such sites would need to meet current environmental protection and radiation protection decommissioning standards for protection of groundwater and the public. In some cases, the heap-leaching waste could be used as a suitable first cover for mill tailing wastes, if the properties of the waste are not too acidic.

Mill Tailings Reclamation

Remediation of mill tailings sites is closely affiliated with reclamation of uranium mines. Mill tailings have been regulated as byproduct materials by the NRC or its Agreement States, and the Department of Energy (see Appendix VI), under the requirements of UMTRCA. Decommissioning of uranium mills follows the environmental protection standards of EPA, and licensing and closure regulations and guidances of NRC or its Agreement States. For at least two sites, mill tailings were stabilized in an engineered cell within a former uranium mine pit on the mill site. Internationally, two types of systems have been used for close-out of tailings impoundments to prevent radon emanation: dry-cover and water-cover systems. Only the dry-cover system is used in the U.S.; however, for information purposes only, the wet-cover system is also described briefly.

Dry-Cover Systems
A dry-cover system utilizes the following steps: (1) removal of free water and stabilization of the surface, (2) recontouring and landscaping of above-ground tailings facilities, (3) capping, and (4) revegetation (if possible) and maintenance. Tailings are usually disposed of as slurry, and water collects on the surface over time as the tailings consolidate and settle. In cases where the tailings have been allowed to spread without containment, physical relocation for consolidation purposes may be preferable. Many mill tailings impoundments have simply been capped with dry rock without revegetation.

Once the containment area has been determined to be acceptable, the water is generally pumped off the tailings, and a cover applied. One method of improving the drainage of tailings is to insert vertical wick (cords or fibers that draw liquid to them) drains, which often allows the tailing mass to reach a lower, final water content than can be achieved by natural drainage. An alternate way of enhancing dewatering of the tailings is to apply a thin layer of high-density cover material. For example, using a layer of

synthetic geotextile and an iron netting increases the surface stability and prevents cracks by compressing the tailings to expel water.

The second step, recontouring the above-ground tailing facilities, improves both the long-term stability of the cover and landscape integration. This step requires that all settling has occurred prior to recontouring. In many cases, particularly for uranium mills, due to arid climate and lack of natural soil, revegetation is not possible and a rock cover may be installed. A principal standard for installation of such a rock cover is U.S. NRC (2002) NUREG-1623, *Design of Erosion Protection for Long-term Stabilization*. The installation of a suitable cap not only covers the waste material, but also prevents fugitive air emissions by covering the particulate that could be mobilized through air currents. The same cap design, water management, re-vegetation, and maintenance issues that apply to waste pile remediation apply to placement of a dry-cover system for tailings remediation.

Water-Cover Systems
While used in Canada and Europe, and in isolated instances for other types of mines in the U.S., water cover is not viewed as an acceptable means of remediation for uranium mill tailings in the U.S., is not permitted under NRC regulations unless approved as temporary water covers (groundwater evaporation ponds), and should not be viewed as EPA recommended procedures. The methods used in other countries are site specific and dependent on environmental impacts, land use requirements, etc. The discussion below is for information purposes only.

A water-cover system completely immerses the waste with a sustainable, thin layer of water. Its objectives are similar to those of a dry-cover system, in that it seeks to stop wind erosion of the dry beaches, reduce radon emanation, provide a barrier to intrusion of the tailings, and prevent acid formation in cases of acid-generating tailings. Covering the tailings with water can prevent contact with atmospheric oxygen and foster the development of anaerobic conditions, which can reduce the mobility of many contaminants of concern. To be considered for a water-cover remedy, a facility may either be an above-ground impoundment where slurry has been allowed to settle, with the slimes settling slowly in the center of the decantation pond, or a below-grade site in open-pits where tailings have been transported as a thickened paste and disposed of.

This technique has several potential problems, including sustaining the water cover, preventing human and biota intrusion from ingesting the water cover, and preventing further contamination of other water bodies through infiltration. A principal issue is mobility of uranium and other radionuclides, especially in either acidic or alkaline waters. As with all potential remediation techniques, the likely effectiveness of techniques such as this need to be seriously evaluated prior to remediation design.

Other Approaches
Internationally, tailings have also been disposed of in natural lakes. Reclamation in those cases focused on ensuring that the tailings would remain contained by the addition of capping with sand and rock. Water quality monitoring programs for lakes have also been implemented in those countries where this disposal method has been used. Such methods have not been approved by the EPA. Tailings that have been placed below ground (in the mine) during operations have provided a long-term management solution from the viewpoint of reducing potential radiation exposures to members of the public. However, the possibility of leaching and suffusion (spreading) by permeating groundwater may need to be taken into consideration. Reclamation and remediation efforts vary based on site specific characteristics, impacts on the environment, and available resources. Options employed for prevention of leaching and suffusion into surface and groundwaters include sealing open mine shafts and creating underground barriers by injecting grouts.

The Wastewater Problem

Water is one of the principal pathways for dispersal of uranium mining pollutants into the environment. Water is contaminated by surface runoff from overburden and waste rock piles, seepage through overburden and waste rock piles, and other actions where mining waste comes in contact with water. The radioactivity is derived from uranium, thorium, radium, lead and daughter products either dissolved or suspended in water. Where pyrite and other sulfidic minerals are present, acidic solutions may be generated. Acid generation, also known as acid mine drainage or acid rock drainage, is a concern of several types of mining. The acidic solutions, which increase the mobility of heavy metals and radionuclides in the ore, require neutralization before being discharged into the environment. Also present in the contaminated water may be nitrates, nitrites, and ammonia originating from the residue of explosives used. The composition of the wastewater is determined by the ore type and grade, and by the process technology used to mine the ore.

Pit water, or pit lake water, is water which has filled an open-pit mine excavation, usually derived as water from underground workings of the mine. As a subset of wastewater, pit water may represent the largest volume of wastewater present from the existence of uranium mines. Pit water can vary greatly in the concentration of contaminants present, and the water in some pit lakes may even meet EPA drinking water standards (Leshendok 2004). However, the resulting water may also have the same general characteristics as other wastewater generated by contact with mining waste or uranium ore. Pit lakes have increasingly become a concern of some state regulators in that these waters are generally open to the public and terrestrial and avian life. For many of these waters, remediation may be a delicate tradeoff due to the vast quantity of the water and the limited tools available for remediation. In some instances the regulatory body may acknowledge an inability to meet human health water quality standards and may refer to other achievable water quality standards such as those sufficient to sustain livestock. The techniques for remediation of these waters are included in the discussion of the techniques that follow.

Setting of quality objectives for aquifers and the surface water courses are established according to federal regulatory requirements, land-use plans, as well as state, Tribal and local rules. There are specific EPA groundwater discharge standards for uranium, thorium, and vanadium, as well as other types of hard rock mines (see Appendix VI), and many states have used these to establish their own standards, with discharge permits required for mines in accordance with the Clean Water Act. Acceptable treatment technologies for mine reclamation are approved by state, Tribal and/or federal agencies (depending on land ownership) according to the nature of the contaminants, their concentrations, and the desired effluent levels. A general objective of regulating agencies for mining water treatment is to produce an acceptable water quality of the discharge with low volumes of residues.

Processes for Treating Uranium Ore

When water comes in contact with uranium bearing ore either naturally in the ground, or when extracted under license by regulated processes, several oxidation reactions take place. The end product of these reactions is uranium sulfate (UO_2SO_4), which creates uranium cake, sulfuric acid, and ferrous sulfate, which are the major wastewater contaminants needing treatment. Additionally, the following chemicals can be generated, either purposely or inadvertently, by chemical reactions occurring with the ore releasing additional contaminants to the wastewater:
- Bicarbonates generated due to treatment of the acidic water with lime.
- Sulfates generated from the oxidation processes described above.

- Chlorides added to process water as a stripping agent in the solvent extraction process from back-washing of ion-exchange resins.
- Nitrates generated from explosives used for rock blasting and fertilizers used in re-vegetation.
- Nitrites and ammonium generated from the degradation of organic pollutants.
- Calcium generated as a residue of water treatment with lime.
- Sodium generated from the solvent-extraction and ion-exchange processes.
- Iron generated from the oxidation of pyrite (FeS_2) and other ferrous sulfides.
- Manganese generated naturally from various weathering processes, but also added as an oxidant in some leaching processes.

Water Treatment Techniques

Treatment of contaminated mine wastewater is usually required, with release concentrations being 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 feet^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 remaining from the wastewater treatment must be disposed of appropriately as determined by the federal, state, or Tribal land management agency, 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.

Methods used for treating mining wastewater include various types of precipitation methods used to settle out the contaminants from the wastewater. These contaminants may include radionuclides, metals, and other inorganic materials. Precipitation methods are the most widely used methods for treating uranium mining wastewater because they use small amounts of chemicals and are cost-competitive. However, they also generate large volumes of residues.

Lime Treatment
Lime treatment is the method of choice for treating acidic waters from uranium processing plants that rely upon sulfuric acid (H_2SO_4) leaching for the extraction of uranium from the ore. It is used for treating acid mine drainage and seepage water from acid uranium mill tailings and other disposal facilities. This process adds a 15–20 percent calcium hydroxide (lime, or COH) slurry to the acid effluent to raise the solution's pH to ten. It blows air into the solution to oxidize ferrous iron, trivalent manganese, and arsenic, and uranium is precipitated out as calcium diuranate. The effluent can then be discharged with dilute sulfuric or hydrochloric acid, after pH adjustment to between six and eight. The underflow[1] containing the metal precipitates is stored for disposal or further treated.

This process produces underflow or sludge of two percent solids, which may be difficult to dewater. While the volume of the underflow can be reduced with drum or disk filters or through centrifuges, the capital and operating costs of this further treatment are high. Another process for minimizing the amount of underflow of sludge generated is to treat the underflow with a high-density sludge (HDS) process. The HDS process uses multi-stage treatment processes and recycled underflow to yield a sludge concentration of up to 15 percent solids.

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[1] Flowing bottom waters containing dissolved or suspended solids.

Ferric Chloride Treatment

Although most of the arsenic (As) present in wastewater is precipitated out with lime treatment, the remaining arsenic levels in the water may still exceed acceptable release limits. If this is the case, ferric (Fe) chloride (Cl) treatment can be added to the slurry during bulk neutralization to precipitate out arsenic. The reaction:

$$AsO_4^{3-} \text{ (aq)} + 3H^+ \text{ (aq)} + FeCl_3 \text{ -------------> } FeAsO_4 + 3HCl \text{ (aq)}$$
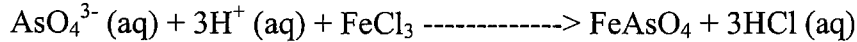
occurs in solutions with a pH of less than seven. Ferric hydroxides also aid in the precipitation process. This process will yield wastewater with concentrations below 0.1 mg/L

Barium Chloride Treatment

Barium chloride ($BaCl_2$) treatment is widely used in the uranium industry to remove radium at mining sites. Radium concentrations below 8.1 pCi/L (0.3 Bq/L) can easily be achieved for wastewater containing sulfate ions. At pH values between six and eight, barium sulfate($BaSO_4$) has a low solubility and readily precipitates out, co-precipitating radium at the same time. Only 0.00007–0.00013 lb (30–60 mg) of barium chloride per liter of wastewater will achieve 95–99 percent removal of radium. Because the resulting crystals are difficult to retain, they are usually co-precipitated with other species during bulk neutralization.

Ion Exchange and Adsorption

Ion exchange is the use of organic or inorganic solids that have chemically reactive sites that are either positively (cations) or negatively (anions) charged to bind with contamination, thus eliminating it from the effluent water. Attached to the reactive groups are easily displaceable ions of the opposite charge. The exchange reaction is driven by the relative concentrations of the competing ions, their electric charge, and their relative affinity for the exchange site. After treatment of the wastewater, when the resins are spent (loaded with the ions to be removed from the wastewater), the ions can be recovered by regenerating the resins by back-washing them with strong acids. Most industrially used ion exchangers are based on synthetic resins, but inorganic substrates such as zeolites are also used. Ion exchange technology is very expensive and is best used for specialized, high-selectivity contaminant removal. The advantages of ion exchange are its ability to treat a wide variety of contaminants and to reduce contaminants to very low levels.

Ion adsorption is similar to ion exchange, except that it does not attempt to regenerate the resins. An example of ion adsorption is a uranium-specific, high-molecular polymer called GOPUR 3000, which has been developed in Germany for removing uranium from wastewater. At pH values between four and eleven, the reactive surfaces undergo chemical change with the uranyl ion, and the resulting insoluble matrix precipitates out of the solution. The sludges can then be dewatered using conventional dewatering techniques.

Bioremediation

In this process, nutrients are added to a water body to increase natural bacterial growth which may then fix the radionuclides and metals in the bacteria, removing them from the water, and eventually settling to the bottom.

A recent example of using bioremediation occurred for a pit lake containing over one billion gallons (3.8 billion liters) of water at the Sweetwater uranium property in Wyoming (Paulson 2004).

Sugars, fats, alcohols, and phosphates were added to the water in quantities approaching one million pounds (about 454 thousand kilograms) over a nine month period. Natural bacteria in the lake

metabolized the nutrients and respired on dissolved materials in the water in this order: dissolved oxygen, nitrates, selenium complexes, dissolved uranium. Dissolved metals precipitated on the lake bottom, increasing the metals concentrations in the bottom sediments. Phosphate addition encouraged the growth of algae which provided a source of organic carbon to maintain the lake. The finished water quality met Wyoming state standards for livestock use. Other experiments such as Anderson et al. (2003) have shown promise with use of metal reducing bacteria, referred to as *Geobacter* species, which can fix uranium in groundwater provided sufficient other nutrients are added to the water. In that study, the microbes were inserted through injection wells to reduce the uranium content of contaminated groundwater at a former uranium mill site in Rifle, Colorado.

Permeable Reactive Barriers
A method which is being used at some Superfund sites, including those with water contaminated with uranium, is the permeable reactive barrier. This technology is a constructed permeable wall installed across the flow path of a contaminant plume, either surface or underground, allowing the water portion of the plume to passively move through the wall. The barrier allows the passage of water while prohibiting the movement of contaminants, including uranium, by employing such agents as granular iron, activated carbon, bacteria, compost or peat, chemicals, and clays. The contaminants will either be degraded or retained in a concentrated form by the barrier material. The wall could provide permanent containment for relatively benign residues or provide a decreased volume of the more toxic contaminants for subsequent treatment. As one example of its use (U.S. EPA et al. 2000), EPA, the U.S. Geological Survey, U.S. Bureau of Land Management, and U.S. Department of Energy participated in a joint study of the Fry Canyon site in southeastern Utah for a long-term field demonstration to assess the performance of selected permeable reactive barriers for the removal of uranium from groundwater. That study found that reactive iron (zero-valent iron) removed nearly 100% of uranium in water after it had passed 1.5 feet (0.5 meter) through the three foot (one meter) thick barrier.

Wastewater Preventive Strategies

The objective of preventive strategies is to avoid generation of acidic wastewaters and contaminated water from closed or abandoned mines and to reduce the amount of contamination needing remediation. The planning of mine closure activities generally gives priority to preventive strategies whenever possible. Following are some of the preventive strategies and goals that may be applicable:

Underground Mines
- Avoid mixing good and poor water quality in actively managed mines.
- Allow flooding of decommissioned mines to reduce the atmospheric oxygen available and the mobilization of contaminants if there is no connection from the mine to surface or groundwater.
- Limit groundwater circulation in mines by reducing permeability and hydraulic isolation.
- Seal shafts, boreholes, and other access routes.
- Seal fracture and fissure zones.
- Dam up individual parts of the mine to prevent circulation.
- Use chemically active backfills to create reactive barriers that reduce contaminant migration.

Surface Impoundments of Mine Waste Materials
- Divert surface water by developing channels.
- Cap impoundments to limit infiltration of atmospheric precipitation.
- Place waste materials selectively to facilitate containment.
- Install reactive inter-layers (crushed limestone) to control pH.

- Encourage the development of anoxic conditions by adding bacterial growth media, such as manure or wood chips.

Open-pits
- Install clay seals to prevent infiltration to underlying strata.
- Add lime to raise pH values.
- Seal boreholes to prevent infiltration into underlying strata.
- Backfill the mine pit to avoid accumulation of surface runoff.

Groundwater Protection at ISL Sites

Environmental regulation of ISL systems is overseen by the NRC or its Agreement States (see Appendix VI); remediation must be conducted to return the groundwater and other systems to as close to pre-extraction conditions, or to the same class of groundwater use as possible. Groundwater protection requirements for ISLs are laid out in NRC's NUREG 1569 (U.S. NRC 2003).

Early experiments in production of underground uranium using the ISL method utilized a variety of different liquids to examine their efficiencies and costs. Used only as a test, it was determined that acidic solution lixiviants (sulfuric acid, nitric acid, and ammonium bicarbonate) destroyed the ore bearing material and mobilized many other unwanted materials. Additionally, the restoration activities were found to be cost prohibitive when attempting to return the aquifer to pre-extraction conditions. Consequently, the industry has moved toward using ISL oxygen, carbon dioxide, or sodium bicarbonate solutions, which have become the predominant form of uranium production in the United States, primarily because of their typically low production costs and expected environmental impacts.

Groundwater restoration is accomplished through a strategy called pump and treat. During ISL, after a 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 now must be double lined and must incorporate leak-detection and leachate-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 g/L 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.

Groundwater sweep is initiated when the uranium concentration in the production fluid has dropped to a level where recovery is no longer feasible. During groundwater sweep, the lixiviant (sodium bicarbonate) is discontinued, but the water is still pumped through the recovery wells, displacing contaminated water from the aquifer. As the aquifer is diluted in the concentration of the lixiviant, groundwater sweep becomes less useful.

During water treatment, contaminated water remaining in the ground is brought to the surface and treated, and clean water is pumped back into the wellfield. This treatment continues until the groundwater is restored (normal treatment volumes are two to six times the volume of water in the original aquifer).

At some operations, the restoration is complete after water treatment. However, since the addition of chemicals into the aquifer creates an imbalance, the rock must be returned to a reduced state by adding a chemical reductant, such as hydrogen sulfide. This reducing action usually causes dissolved uranium and other heavy metals to stabilize at acceptable levels.

Circulation is then conducted in the aquifer, where water in the amount of two or three times the volume of the aquifer is pumped though the wells to eliminate spatial and temporal variations in water quality. Finally, stabilization monitoring is conducted to ensure that the well has reached a steady state. If there is no indication of increasing levels of ground water constituents of concern, the site is released for unrestricted use.

Evaporite wastes from evaporation ponds are currently disposed of in facilities licensed to receive such wastes under NRC standards.

Building and Equipment Reclamation

Uranium mine sites usually have very few or no buildings. Any buildings on site are generally temporary and are easily demolished, though some may be constructed of overburden or waste rock, cemented together. Demolished building material has generally been bulldozed into one of the open-pits or sometimes into underground mine portals to be reclaimed and included with the waste rock.

Equipment associated with the conventional mining sites includes mining shaft equipment and frames, rock ore cars, and other equipment that has come in contact with the ore or waste ore material. Radiation contamination of this equipment is generally limited to the residue from the transportation and handling of the mining ore. As such, this equipment has generally been decontaminated by thoroughly washing it with water or other mild cleaning agents. Following the washing the equipment can be transported to another site for reuse, depending on its residual radioactivity level, and state requirements.

However, old equipment generally has very little monetary value. In many cases an effective remediation method has been to simply dispose of the equipment in an open-pit or mine portal and bury it with waste rock. The resulting waste rock and equipment pit are reclaimed by installing a dry cover. In some cases, decontaminated equipment may be sent to a recycling mill for processing into new equipment.

Many abandoned mines may have other types of wastes, such as metals, hydrocarbon spills from storage tanks or vehicle fueling, polychlorinated biphenyls (PCBs) from old or damaged electrical transformers at a site, lab wastes, explosives, and refuse. Those wastes must be cleaned up in accordance with established EPA and state rules for hazardous wastes.

Radiation Protection Standards for Reclaiming and Remediating Uranium Mines and Extraction Facilities

The preceding discussion provided an overview of the process of reclaiming uranium mines and extraction facilities, as well as means of restoration of surface and groundwaters. These same processes are generally used for remediation where hazardous materials are being cleaned up at the site or outside its property borders, except that removal and disposal may be more labor intensive, may require special protections for workers, property and the public, and require long-term monitoring and stewardship to ensure that no future releases of the hazardous materials occur. In a particular circumstance, the U.S.

Congress passed UMTRCA, which established a remedial cleanup program for specific abandoned uranium mills.

Radium-226, thorium-230, and radon-222 (gas), and their decay products are the radionuclides present in uranium mill tailings that are of principal concern to human health and the environment. Under UMTRCA, EPA has the responsibility to establish standards for exposure of the public to radioactive materials originating from mill tailings and for cleanup and control standards for inactive uranium tailings sites and associated vicinity areas, as well as operating sites. EPA's regulations in 40 CFR 192 apply to remediation of such properties and address emissions of radon, as well as radionuclides, metals, and other contaminants into surface and groundwater. Title I of the Act concerns tailings at inactive uranium milling and extraction sites while Title II applies to currently operating uranium mill tailings facilities licensed by the NRC or an Agreement State. More discussion on UMTRCA and associated federal regulations can be found in Appendix VI, and U.S. EPA (1995a). Among the more important remediation standards are:

- The disposal areas must be designed to limit releases of radon-222 from uranium byproduct materials to the atmosphere so as not to exceed an average release rate of 20 $pCi/m^2/s$. This requirement, however, applies only to a portion of a disposal site that contains a concentration of radium-226 that, as a result of uranium byproduct material, exceeds the background level by more than:
  - 5 pCi/g, averaged over the first 15 cm below the surface
  - 15 pCi/g averaged over 15 cm thick layers more than 15 cm below the surface.

- Maximum concentration limits are established for protection of groundwater, although alternative concentration limits can be established for specific sites by DOE. The EPA standards are (in milligrams per liter, unless otherwise stated:

Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Lead	0.05
Mercury	0.002
Selenium	0.01
Silver	0.05
Nitrate (as N)	10.
Molybdenum	0.1
Combined radium-226 and radium-228	5 pCi/liter
Combined uranium-234 and uranium-238 *	30 pCi/liter
Gross alpha-particle activity (excluding radon and uranium)	15 pCi/liter
Endrin (1,2,3,4,10,10-hexachloro-6,7-exposy1,4,4a,5,6,7,8,8a- octahydro-1,4-endo,endo-5,8-dimethanonaphthalene)	0.0002
Lindane (1,2,3,4,5,6-hexachlorocyclohexane, gamma insomer)	0.004
Methoxychlor (1,1,1-trichloro-2,2'-bis(p- 0.1methoxyphenylethane))	0.1
Toxaphene (C10H10Cl6, technical chlorinated camphene, 67-69 2,4-D (2,4-dichlorophenoxyacetic acid) 2,4,5-TP	0.005
Silvex (2,4,5-trichlorophenoxypropionic acid)	0.01

Where secular equilibrium obtains, this criterion for uranium will be satisfied by a concentration of 0.044 milligrams per liter (0.044 mg/l). For conditions of other than secular equilibrium, a corresponding value may be derived and applied, based on the measured site-specific ratio of the two isotopes of uranium.

The NRC or its Agreement States license uranium mills. Under statutory requirements of the AEA and UMTRCA, NRC has issued regulations in 10 CFR Parts 40 and 51 to provide for environmental protection for domestic licensing and related regulatory functions, while those in 10 CFR Part 20 cover radiation protection from hazards of mills and their wastes, and adopt the EPA standards. NUREG 1620 (U.S. NRC 2004) provides guidance for the approval of reclamation plans of active uranium mills.

While EPA has not established radiation protection standards for use in mine reclamation, it has developed guidance for use in cleanup of radioactively contaminated soils and groundwater primarily for the Superfund program. The soil standards are based on the use of radiation standards developed under the UMTRCA program for uranium mills (U.S. EPA 1998, 1997c) while cleanup standards for groundwater use EPA's maximum contaminant levels established under the Safe Drinking Water Act (U.S. EPA 2001c). The radionuclide soil cleanup standard for combined radium-226, radium-228, and thorium-232 is 5 pCi/g. For groundwater cleanup and protection, the EPA drinking water standards for uranium of 30 µg/L, and 5 pCi/L for radium are relevant and appropriate.

Costs of Reclaiming and Remediating Uranium Mines and Extraction Facilities

The discussion which follows provides a brief overview of the costs of reclamation and remediation at uranium mines and extraction facilities (mills, ISL and heap-leach). Analysis of reclamation and remediation costs at uranium mines and extraction facilities would potentially include costs associated with the following items: overburden and waste rock piles, heap-leach piles, ore storage and loading areas, tailings ponds, underground mines, open-pit mines, milling facilities, buildings and infrastructure, ISL infrastructure, and contaminated soils and groundwater.

Costs of environmental management after closure consist primarily of reclamation and monitoring costs. For mines, reclamation may include partial or complete backfilling of pits, stabilization of waste rock piles, appropriate contouring of disturbed land surfaces, and revegetation. Monitoring is a post-closure cost of some, but not all mines. Since remediation projects vary greatly due in part to ore conditions, mining and extraction method, climate, remediation scope and objectives (usually as defined by applicable regulations), and sources and availability of funds, the costs for reclaiming uranium mines also vary greatly. In those instances where an operating, inactive or abandoned facility has been remediated as a result of response to releases of hazardous substances under CERCLA or applicable state laws, the costs may be incrementally larger.

The Department of Energy conducted a summary of cleanup costs for 75 production facilities, including mining and milling operations of uranium mines, an abbreviated version of which appears in Tables 4.1–4.4. Due to the similarity of the cleanup techniques, costs for remediating uranium milling sites (under UMTRCA) have been included in Tables 4.1 to 4.3. The costs of reclaiming and remediating the 21 mines included in this survey varied widely, by more than two orders of magnitude in terms of cost per ton of ore and kg of uranium produced (Table 4.4). Some of this range is attributable to the differences in acreage of land area disturbed per ton of ore, but much of it is due to the differences in methods of accounting for cleanup costs. Some of the mines performed contemporaneous reclamation during mining. Some of those mines charged those costs against operations, while others charged them separately as reclamation costs.

The average costs of cleanup of the 21 mine sites included in this survey were $3.01/metric ton (MT) of ore mined, $2.54/kg of uranium produced, and $29,969/hectare of land disturbed. However, the Day-Loma mine has exceptionally high costs and skews the averages disproportionately to its total production. If Day-Loma cost figures are excluded, the Title II average costs drop to $2.77/MT of ore, $2.34/kg of uranium produced, and $27,900/hectare of disturbance. Costs of reclamation of these sites ranged from a low of $0.24/MT of ore, $0.18/kg of uranium produced, and $2,337/hectare disturbance to a high of $33.33/ MT of ore, $23.74/kg of uranium produced, excluding the Day-Loma mine, and $269,531/hectare disturbance for all 21 mines. The average total estimated cost is $13.9 million per mine.

**Table 4.1. Total and Average Production and Costs of Remediation
of TITLE I Uranium Mills and Related Facilities**
Title I Mills were abandoned, un-licensed mills operated during the AEC existence.

Number of sites included	26
Metric tons of ore processed	29,100,000
Metric tons of uranium produced	50,624
Average cost of closure, $/MT ore	$50.91
Lowest cost of closure, $/MT ore	$5.00
Highest cost of closure, $/MT ore	$320.25
Average cost of closure, $/kg U	$29.22
Lowest cost of closure, $/kg U	$2.50
Highest cost of closure, $/kg U	$348.42
Average cost of closure, $/curies Ra-226	$48,000
Lowest cost of closure, $/curies Ra-226	$5,000
Highest cost of closure, $/curies Ra-226	$958,167
Average closure cost per site	$56,900,000
Total closure costs of all Title I sites —excluding groundwater program	$1,480,000,000
Title I Groundwater Program	$215,000,000
Total Closure Costs of all Title I Sites	**$1,695,000,000**

Source: U.S. DOE/EIA 2000b.

**Table 4.2. Total and Average Production and Costs of Remediation
of TITLE II Uranium Mills and Related Facilities**

Title II Mills were mills licensed by NRC or Agreement States in or after 1978.

Number of sites included	28
Metric tons of ore processed	220,000,000
Metric tons of uranium produced	284,088
Average cost of closure, $/MT ore	$2.66
— excluding Shootaring Canyon Mill	$2.62
Lowest cost of closure, $/MT ore	$0.67
Highest cost of closure, $/MT ore	$11.33
Average cost of closure, $/kg U	$2.06
— excluding Shootaring Canyon Mill	$2.03
Lowest cost of closure, $/kg U	$0.45
Highest cost of closure, $/kg U	$14.04
Average Closure Cost per Site	**$20,900,000**
Total Closure Costs of All Title II Sites	**$584,800,000**

Source: U.S. DOE/EIA 2000b.

**Table 4.3. Total and Average Production and Costs of Reclamation
of All Uranium Mill Sites (Title I and Title II)**

Average Closure Cost per Site	**$42,200,000**
Total Closure Cost	**$2,279,800,000**

Source: U.S. DOE/EIA 2000b.

Table 4.4. Total and Average Production and Costs of Reclamation of All Uranium Mines
This table includes mines as well as mill sites.

Number of sites included	21
Metric tons of ore processed	96,900,000
Metric tons of uranium produced	114,803
Average cost of closure, $/MT ore	$3.01
— excluding Day-Loma	$2.77
Lowest cost of closure, $/MT ore	$0.24
Highest cost of closure, $/MT ore	$33.33
Average cost of closure, $/kg U	$2.54
—excluding Day-Loma	$2.34
Lowest cost of closure, $/lb U3O8	$0.18
Highest cost of closure, $/lb U3O8	$23.74
Average cost of closure, $/ha disturbance	$29,969
—excluding Day-Loma	$27,900
Lowest cost of closure, $/ha disturbance	$2,337
Highest cost of closure, $/ha disturbance	$269,531
Average Closure Cost per Site	**$13,900,000**

Source: U.S. DOE/EIA 2000b.

At a similar level of expenditure, remediation by EPA of the Lucky Lass and White King uranium mines in Oregon under CERCLA was estimated to cost approximately $8 million (U.S. EPA 2001a). The National Forest Service planned to remediate the Juniper uranium mine in California at a cost of approximately $2 million (AAPG 2005).

Underground and open-pit mine closures which have not involved remediation or long-term monitoring have been reported by some organizations as costing significantly less than the above sites, particularly when overburden, waste rock, and protore have not needed to be disposed off-site, soil contamination is minimal, sites are relatively small, and water intrusion has not been a problem. For example, the Navajo Abandoned Mine Lands Agency (Navajo AMLR 2000) expended about $893,000 to reclaim 20 mines with over 245 mine portals, over 57,000 cubic yards of radioactive mine waste spread over 35 acres of land, and seven acres of haul road. The average cost per mine would be about $45,000.

On the other hand, remediation actions under CERCLA for spilled ore off-site of a mine can be expensive. 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 (about 29 km) distant, amounted to a cost of approximately $357,500 (MFG 2005).

U.S. DOE/EIA (1995) estimated average decommissioning costs for ISL operations were $7 million. Groundwater restoration accounted for $2.8 million, wellfield reclamation costs were $0.9 million and the plant dismantling costs came to $0.6 million. Other costs (such as evaporation ponds, disposal wells, and radiological surveys) averaged $1.2 million. The indirect costs averaged $1.4 million.

Stewardship and Long-Term Monitoring, Management and Remediation

Radiation from closed sites remains a potential risk concern for thousands of years due the extensive half-lives of uranium isotopes and their progeny. Even when state-of-the art remediation methods have been used for stabilizing a site, proof that the methods have been successful can sometimes only be obtained through long-term monitoring of air and water pathways. Because some uranium mines are developed where natural accumulations of uranium far exceed normal concentrations in unmineralized rocks, areas in and around uranium mines have natural, ambient radioactivity that may be hazardous to human health, irrespective of whether a mine was ever developed.

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. 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). Under UMTRCA requirements, reclaimed uranium mill tailings sites are licensed to the DOE and designed for 1000 years of control.

Stewardship refers to the institutional controls (ownership or governmental) which may be put in place to ensure that a specific site meets its closure goals. Institutional controls can be either active, involving some form of continuous or intermittent human activity to maintain the condition of the site, or passive, which do not require human intervention and have an amount of redundancy built into them to deter or prevent disturbance of the remediated site. Examples of active controls are air, surface, and groundwater monitoring; site inspections; ground radiation surveys; and aerial gamma surveys. Examples of passive controls are land-use restrictions, fences, and signs. The installation of passive controls does not negate the need for active institutional controls (i.e., monitoring).

Stewardship may also include reclamation goals other than protecting human health and preventing water pollution. Some may include consideration of providing bat gates for underground mines, ensuring little or no disruption to wildlife using or passing over the site, staining highwall rock to reduce visual impacts, and ensuring there are no reclamation impacts on historical or cultural sites. These may be built into closure requirements for sites.

Monitoring for uranium mining and extraction sites, if required, allows for the assessment of the effectiveness of the reclamation and remediation efforts. Although requirements may differ, some of the more common approaches include the following:
- Site inspections confirm that the integrity of the site has not been disturbed.
- Geotechnical monitoring, sometimes involving global positioning systems, identifies the site and determines if any settling, erosion, or movement has occurred.
- Groundwater monitoring for uranium and other contaminants detects contaminant movement into groundwater systems.
- Surface water monitoring detects changes in the quality or quantity of surface water.
- Air monitoring detects increases in radon and other emissions from the site.

- Ecological monitoring determines if any of the biota are affected by bioaccumulation of heavy metals or radionuclides from the remediated site.

There have been situations where long-term active actions may be required to maintain wastewater treatment facilities or fences, provide for possible future groundwater or air impacts, etc. Several hardrock mines—both new and abandoned—have had to have long-term planning and funding developed to ensure that at some time in the future such impacts are properly managed (Leshendok 2004).

The time period over which monitoring can be required depends on a number of factors, not the least of which is funding availability. Contemporary remediation designs have been developed with a projected lifetime of 200 or 1,000 years (uranium tailings sites must be designed for 1,000 years of control, and disposal sites must be designed for 200 years of control). Older sites did not have an established design parameter for the design of these plans. Site monitoring, if necessary, may initially be conducted every year. However, if little change is noted, the frequency may be reduced to every other year or even once every five years. Generally, if the monitoring phase indicates no increasing levels of radionuclide or pollutant discharge, sites have been released for unrestricted use.

Chapter 5. Conclusion

Uranium, a naturally occurring element, contributes to low levels of natural background radiation in the environment, and is found in virtually all rock and soil, as well as ground water. Contained in a variety of ore bearing rocks, it can be extracted and chemically converted into uranium oxide or other chemical forms usable in industry. Uranium undergoes radioactive decay into a long series of different radionuclides before finally reaching a stable state as lead. These radionuclides each emit alpha or beta radiation, and some also emit gamma radiation of widely varying energies. Some of these progeny radionuclides are highly radioactive and can pose significant human health risks, most notably radium and the radioactive gas radon.

Mining is the process by which mineral and metal bearing ores are extracted from the earth. 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. Radioactive waste materials for which EPA, Tribal, state, or local government agencies have statutory authority, that are or could be classified as TENORM from conventional open-pit and underground uranium mining include overburden (although most overburden is not necessarily enriched in uranium as is protore), unreclaimed protore, waste rock, evaporites from mine water, mine and pit water, drill core and cuttings, and refuse. Liquid and solid waste materials generated at heap leaching, ISL, or uranium mills are considered byproduct that is regulated by the NRC or its Agreement States.

Most uranium mining in the United States took place in the Colorado Plateau region straddling the Four Corners where Utah, Colorado, New Mexico, and Arizona meet, though more than a dozen states have hosted uranium mines during the last century. Significant changes in the uranium market price for uranium after the early 1980s previously resulted in inactivation or closing nearly all mines and uranium mills in the country. Recent increases in uranium price and demand have resulted in renewed interest in re-opening mines that were closed or on standby. While some mines focus on extraction of just uranium minerals, many mines have produced uranium along with a host of other valuable minerals that were found together in the same rock ore.

The early small mining endeavors generated small quantities of waste typically discarded within a few to hundreds of feet (100 meters) of the mine opening or pit. Major surface mines tend to disturb large surface areas from the extent of both the pit and the spoils areas. Generally, tens to hundreds of acres may be covered by overburden and waste rock. At some sites, as mining progressed, the overburden was used to backfill mined-out areas of the open-pit in anticipation of later reclamation. Most of the older surface mines (pre to-mid-1970s) were not backfilled during mining operations, while some of the more recent mining included modest backfilling operations. The surface area affected by major underground mining activities generally involves less than about 50 acres (20 hectares).

Waste volumes produced by surface, open-pit mining are a factor of 45 greater than for underground mining, based on their respective averages. Thus, the amount of overburden and waste rock generated from open-pit mines far exceeds that from underground mines. The U.S. Geological Survey (Otton 1998) estimated that the total amount of overburden and waste rock generated by the approximately 4,000 operating conventional mines in its data set is from one billion and nine billion metric tons, with a likely estimate of three billion metric tons. Overburden and waste rock from surface mines can include huge boulders that may have been broken down with explosives and heavy machinery into particles ranging from a micrometer to boulders about three feet (a meter) or more in diameter. 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. This may ultimately affect the availability of metals and radioactivity to the environment as contaminants.

Radionuclide leaching primarily from mine waste piles adjacent to open-pit mines—but also possibly derived by leaching from mine pit walls or by groundwater infiltration from underlying uranium deposits—can result in significant levels of radiation in water-filled pit lakes, though some pit waters may not become very contaminated. Surface and underground mines that intersect aquifers have the potential to contaminate the aquifers.

In the 1980s, primarily due to cost, ISL operations, which began in the 1970s, displaced surface and underground mining methods as the principal means of extracting uranium in the United States. In general, ISL generates small amounts of surface solid waste comprised of: (1) soil and weathered bedrock material disturbed during surface preparation of the site, (2) liquid and solid waste from drilling of injection and production wells, and (3) solids precipitated during storage and processing of fluids in holding ponds. Available data are insufficient to estimate the total amount of solid and liquid wastes generated by existing and previous ISL operations.

Some uranium mines pose such a hazard that they are Superfund sites. Two uranium mines are on the National Priorities List, and CERCLA removals were undertaken in 2001 for two houses constructed with uranium mine waste rock on Tribal lands, and a recent removal action took place in Washington state for off-site spills of uranium ore materials along a haul road between a mine and a mill. The reclamation and remediation of uranium mines is an important consideration when contemplating the impact of past and present uranium mining operations. Data from a Department of Energy/Energy Information Administration study reveal that the costs of reclamation without site monitoring ranged from a low of $0.24/MT of ore, $0.18/kg of uranium produced, and $2,337/hectare of disturbance to a high of $33.33/MT of ore, $23.74/kg of uranium produced, and $269,531/hectare of disturbance for all 21 mines. 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 mine-scarred lands currently unreclaimed, especially in arid regions, may require much lower remediation costs. on the order of $45,000 or lower; 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.

When conventional mining and uranium extraction facilities are closed, stewardship and monitoring may be required for long periods of time to ensure that reclamation and remediation goals have been met, depending on regulatory agency requirements. However, in many cases, once a facility has been reclaimed and there are no indications of increasing levels of radionuclide or pollutant discharge, it is considered released for other uses.

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Appendix I. List of Acronyms and Abbreviations, and Glossary of Terms

List of Acronyms and Abbreviations

Ac	actinium
ac	acre
ac-ft	acre-feet
ACAA	American Coal Ash Association
AEA	Atomic Energy Act
AEC	Atomic Energy Commission
ALARA	As low as reasonably achievable
AML	abandoned mine lands
As	arsenic
ATSDR	Agency for Toxic Substances and Disease Registry
Ba	barium
BASINS	Better Assessment Science Integrating Source and Non-point Sources (USGS computer model)
BAT	best achievable technology
Bi	bismuth
BPCT	best practicable control technology
Bq/kg	Becquerel/kilogram.
BRC	Bureau of Radiation Control
CAA	Clean Air Act
$CaSO_4$	calcium sulphate (formula for gypsum)
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act (Superfund)
CFR	Code of Federal Regulations
Ci	Curie(s) (unit of radioactivity, 3.7 x 10^{10} disintegrations per second)
cm	centimeter
COD	chemical oxygen demand
Cr	chromium
CRCPD	Conference of Radiation Control Program Directors
Cu	copper
CWA	Clean Water Act
D&D	decontamination and decommissioning
DOE	Department of Energy
DOI	Department of the Interior
dscm	dry standard cubic meter
E	used to denote exponents (3.7E+10)
EIA	Energy Information Administration (U.S. Department of Energy)
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute
°F	degrees Fahrenheit
Fe	iron
$FeCl_3$	ferric chloride
FeP	ferro-phosphorus
FeS_2	pyrite
FIPR	Florida Institute of Phosphate Research
Fr	francium

ft	feet
g	gram
g/cm^3	gram per cubic centimeter
Gy	Gray
H	hydrogen
ha	hectare, 2.471 acres
HDS	high-density sludge
Hg	mercury
hr	hour
ISL	*in situ* leaching
K	potassium
K_d	element-specific soil–water partition coefficient
kg	kilogram
L	liter
LTSP	long-term surveillance plan
μ	micro, 10^{-6}, used in combination with specific units
$\mu g/m$	microgram per meter
$\mu g/m^3$	microgram per cubic meter
μm	one-millionth of a meter (micron)
$\mu R/hr$	microRoentgen per hour
m	milli, 10^{-3}, used in combination with specific units
m	meter
m^2	square meter
m^2/s	square meters per second
m^3	cubic meter
MAS/MILS	Minerals Availability System/Minerals Industry Location System (USGS database)
mbd	million barrels per day
MCL	maximum contaminant level
mg	milligram
mL	milliliter
Mn	manganese
Mo	molybdenum
MOU	memorandum of understanding
mrem	millirem
mR/hr	milliRoentgen per hour
mSv	milliSievert
MT	metric ton(s), 1000kg, or 2,200 lb
MMTs	millions of metric tons
n	nano, 10^{-9}, used in combination with specific units
NAAQS	National Ambient Air Quality Standards
NAMLRP	Navajo Abandoned Mine Lands Reclamation Program
NARM	naturally occurring and accelerator-produced radioactive material
NAS	National Academy of Sciences
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act
NESHAP	National Emission Standards for Hazardous Air Pollutants
NFS	National Forest Service
NNEPA	Navajo Nation Environmental Protection Agency
NORM	naturally occurring radioactive material
NPDES	National Pollutant Discharge Elimination System

NPL	National Priorities List
NPS	National Park Service
NRC	Nuclear Regulatory Commission
NSPS	New Source Performance Standards
O_2	oxygen
ORIA	Office of Radiation and Indoor Air (U.S. EPA)
OSM	Office of Surface Mining
p	pico, 10^{-12}, used in combination with specific units
Pa	protactinium
Pb	lead
pCi/g	picocurie per gram
pCi/L	picocurie per liter
pCi/m^2/s	picocurie per meter squared per second
pH	negative log of hydrogen ion concentration (measure of acidity and alkalinity)
Po	polonium
ppb	parts per billion, 10^{-9}
ppm	parts per million, 10^{-6}
Pu	plutonium
QA/QC	quality assurance/quality control
R	Roentgen
r^2	correlation coefficient
Ra	radium
RCRA	Resource Conservation and Recovery Act
Rem	Roentgen equivalent in man
RESRAD	computer model to evaluate risks/doses from RESidual RADiation materials (DOE's Argonne National Laboratory)
ROD	record of decision (Superfund)
s	second
SAB/RAC	Science Advisory Board/Radiation Advisory Committee (with U.S. EPA)
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
Se	selenium
SEO	State Engineer's Office
SIP	State Implementation Plans
SMCRA	Surface Mining Control and Reclamation Act
Sr	strontium
SSL	soil screening level, in pCi/g
Sv	Sievert
tpd	tons per day
TDS	total dissolved solids
TENORM	technologically enhanced, naturally occurring radioactive material
Th	thorium
Tl	thallium
TNRCC	Texas Natural Resources Conservation Commission (now Texas Commission on Environmental Quality)
TRC	Texas Railroad Commission
TSD	treatment, storage, and disposal
TSS	total suspended solids
TWC	Texas Water Commission
U	uranium
U_3O_8	oxide of uranium

$U_4+Ti_2O_6$	brannerite
UIC	underground injection control
UMTRA	Uranium Mill Tailings Remedial Action program (U.S. DOE)
UMTRCA	Uranium Mill Tailings Radiation Control Act of 1978
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UO_2	uranium dioxide
UO_2SO_4	uranium sulfate
$USiO_4\text{ß}n\text{H}_2\text{0}$	coffinite
U.S. ACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
y^3	cubic yard(s)

Glossary of Terms

Adits	Horizontal or nearly horizontal passages driven from the surface for the working or dewatering of a mine. If driven through a hill or mountain to the surface on the other side it would be a tunnel.
ALARA	Acronym for As Low As Reasonably Achievable: A basic concept of radiation protection which specifies that exposure to ionizing radiation and releases of radioactive materials should be managed to reduce collective doses as far below regulatory limits as is reasonably achievable considering economic, technological, and societal factors, among others.
Alpha Particle	A positively charged particle emitted by some radioactive materials undergoing radioactive decay. A helium nucleus (two protons and two neutrons)
Aquifer	An underground geological formation, or group of formations, containing water. Sources of groundwater for wells and springs.
Background	Radiation from cosmic sources, naturally occurring radioactive material, including radon (except as a decay product of source or special nuclear material), and global fallout as it exists in the environment from the testing of nuclear explosive devices or from nuclear accidents like Chernobyl which contribute to background radiation and are not under the control of the cognizant organization.
Becquerel (Bq)	The International System (SI) unit of activity equal to one nuclear transformation (disintegration) per second. 1 Bq = 2.7×10^{-11} Curies (Ci) = 27.03 picocuries (pCi).
Berm	A horizontal shelf or ledge built into the embankment or sloping wall of an open pit, quarry, or ground surface to break the continuity of an otherwise long slope and to strengthen its stability or to catch and arrest slide material.
Beta Particle	An electron emitted from an atom's nucleus during radioactive decay.

Beneficiated	The initial attempt at liberating and concentrating a valuable mineral from extracted ore. This is typically performed by employing various crushing, grinding and froth flotation techniques. The remaining (beneficiated) material is often physically and chemically similar to the material (ore or mineral) that entered the operation, except that particle size reduction has often occurred.
Bioremediation	The use of biological agents, such as bacteria or plants, to remove or neutralize contaminants, as in polluted soil or water.
Brannerite	A radioactive uranium bearing mineral, $(U,Ca,Y,Ce)(Ti,Fe)_2O_6$
Breccia	A coarse-grained clastic rock, composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix. Breccia may originate as a result of talus accumulation, explosive igneous processes, collapse of rock material, or faulting.
Byproduct Materials	Tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes. Underground ore bodies depleted by such solution extraction operations do not constitute "byproduct material" within this definition.
Carbonates	A sediment or sedimentary rock formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron; e.g., limestone and dolomite.
Cleanup	Actions taken to deal with a release or threatened release of hazardous substances that could affect public health or the environment. The term is often used broadly to describe various Superfund response actions or phases of remedial responses, such as remedial investigation/feasibility study. Cleanup is sometimes used interchangeably with the terms remedial action, response action, or corrective action.
Coffinite	A naturally occurring uranium mineral, $U(SiO_4)_{1-x}(OH)_{4x}$
Consolidated	In geology, any or all of the processes whereby loose, soft, or liquid earth materials become firm and coherent, either cemented or non-cemented together.
Contamination	The presence of residual radioactivity, heavy metals or other pollutants in excess of levels which are acceptable for release of a site or facility for unrestricted use.
Core Sample	A soil, rock, or sediment sample taken by core drilling.
Conventional Mining	Mining which uses either mechanical open-pit surface mining methods, or underground mining methods, or a combination of both, to extract ore

	from the ground. This is opposed to unconventional or solution mining methods.
Curie (Ci)	The customary unit of radioactivity. One curie (Ci) is equal to 37 billion disintegrations per second (3.7×10^{10} dps = 3.7×10^{10} Bq), which is approximately equal to the decay rate of one gram of Ra-226. Fractions of a curie, e.g. picocuries (pCi) or 10^{-12} Ci and microcurie (μCi) or 10^{-6} Ci, are levels typically encountered in radiation measurements of NORM or TENORM.
Decline	A downward ramp.
Decommission	To remove a facility or site safely from service and reduce residual radioactivity to a level that permits release of the property and termination of a source materials license and other authorization for site operation.
Decommissioning	The process of removing a facility or site from operation, followed by decontamination, and license termination (or termination of authorization for operation) if appropriate. The objective of decommissioning is to reduce the residual radioactivity in structures, materials, soils, groundwater, and other media at the site so that the concentration of each radionuclide contaminant that contributes to residual radioactivity is indistinguishable from the background radiation concentration for that radionuclide.
Drill Cuttings	The particles of rock produced in a borehole or drill hole by the abrasive or percussive action of a drill bit; erosive effect of the circulating liquid; or cavings from the borehole. At some mines and operations sites, cores of rock from a well or borehole may be left behind as waste—referred to in this report as drill cuttings for convenience.
Drilling Wastes	Wastes associated with a drillhole operation at a mine or extraction facility that are not considered cuttings or cores. May include drill muds or other drilling fluids, sludges, or evaporation products collected in excavated pits from waste water produced during drilling.
Dose	A general term used to refer to the effect on a material that is exposed to radiation. It is used to refer either to the amount of energy absorbed by a material exposed to radiation, or to the potential biological effect in tissue exposed to radiation
Electrodialysis	A means of extracting one or more dissolved materials from a liquid mixture, the process is dialysis assisted by the application of an electric potential across a semi-permeable membrane.
Elution	Process of removing an economic mineral (uranium) from an ion exchange filter or resin.
Evaporative Ponds	Areas where mine water or other produced water is placed and dried by evaporation, leaving a residue of solids or sludges.

Evaporite	An inorganic chemical sediment that precipitates when the salty water in which it had dissolved evaporates.
Excavated Wall	A wall of mineral ore that has been exposed by mining over a considerable width at one time.
Exposure Pathway	The route by which radioactivity travels through the environment to eventually cause radiation exposure to a person or group (e.g., air or water). Also, the route by which a member of the public is exposed (e.g., ingestion, inhalation).
External Radiation	Radiation from a source outside the body.
Extraction Facility	An industrial complex and land on which are located buildings, wells and pipelines, mechanical and chemical equipment, storage and transportation equipment licensed by the Nuclear Regulatory Commission or its Agreement States for the purposes of extracting uranium (source material) in accordance with the Atomic Energy Act.
Extraction Process	A process used to extract uranium from ore, either by milling and chemically treating the ore, or using chemical solutions to treat underground ore (*in situ* leaching), or by treating mined and crushed ore on the surface (heap leaching). These processes are licensed activities by the Nuclear Regulatory Commission or its Agreement States in accordance with the Atomic Energy Act.
Gamma Radiation	Penetrating high-energy, short-wavelength electromagnetic radiation (similar to X-rays) emitted during radioactive decay. Gamma rays are very penetrating and require dense materials (such as lead or steel) for shielding.
Gangue	The valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration.
Garnet	A group of silicate minerals found in igneous rocks, usually red in color, used as a semi-precious stone in crystalline form, or ground into smaller particles and used for abrasives such as in sandpaper coating.
Half-Life ($t_{1/2}$)	The time required for one-half of the atoms of a particular radionuclide present to disintegrate.
Heap-Leaching	A method of extraction by which mineral bearing ores are leached on the ground surface from weathered low-grade ore. The crushed material is laid on a slightly sloping, impervious pad and uniformly leached by the percolation of leach liquor trickling through the beds by gravity to ponds. The metals are recovered by conventional methods from the solution.

| Igneous | Rock or mineral that solidified from molten or partly molten material, i.e., lava or magma. These rocks constitute one of the three main classes into which all rocks are divided: igneous, metamorphic, and sedimentary. |

| Ilmenite | An iron-black, opaque mineral ($FETiO_3$) which is the principal ore of titanium. |

| Incline | A slanting shaft from the surface into an underground mine. Most commonly referring to an upward slope. |

| *In Situ* Leaching (ISL) | A method of extraction by which mineral bearing ores are leached underground by the introduction of a solvent solution, called a lixiviant, through injection wells drilled into the ore body. The process does not require the extraction of ore from the ground. The lixiviant is injected, passes through the ore body, and mobilizes the mineral, and the mineral-bearing solution is pumped to the surface from production wells. The pregnant leach solution is processed to extract the mineral sought after. |

| Ion Exchange | A common water-softening method often found on a large scale at water purification plants that remove some organics and radium by adding calcium oxide or calcium hydroxide to increase the pH to a level where the metals will precipitate out. |

| Lab Waste | Wastes of any kind generated by a laboratory, usually on-site, analyzing rock, sediment, water or other samples obtained at the mine or extraction facility, or its vicinity. |

| Leachate | A solution obtained by leaching; e.g., water that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution. |

| Leach Liquor | Lixiviant which contains minerals dissolved from host rocks. |

| Leuxocene | General term for a fine-grained, opaque, whitish alteration (weathering) product of ilmenite in mineral form. |

| Lithologic | Character of a rock described in terms of its structure, color, mineral composition, grain size, and arrangement of its component parts; all those visible features that in the aggregate impart individuality to the rock. Lithology is the basis of correlation in coal mines and commonly is reliable over a distance of a few miles. |

| Longwall Retreat | A method of mining flat-bedded deposits, in which the working face is mined over a considerable width at one time. The excavation retreats towards the shaft. In this method, all the roadways are in the ore body and the waste areas are left behind. |

| Lixiviant | A liquid medium that selectively extracts the desired metal from the ore or material to be leached rapidly and completely, and from which the desired metal can then be recovered in a concentrated form. |

Mill Tailings	Residue of raw material or waste separated out during the processing of uranium mineral ores. Byproduct material in accordance with the AEA.
Mine	Mining is the mechanical process by which mineral ores are extracted from the earth.
Mine Footprint	The areal extent of land physically disrupted by a mine operation.
Mineral Sands	Eroded and generally unconsolidated sedimentary particles of rock minerals of sand size which have accumulated in a geologic deposit, and may be exploited or concentrated for economic purposes.
NORM	Naturally Occurring Radioactive Materials. 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.
Ore	The naturally occurring material from which a mineral or minerals of economic value can be extracted profitably or to satisfy social or political objectives. The term is generally but not always used to refer to metalliferous material, and is often modified by the names of the valuable constituent; e.g., iron ore; ore mineral.
Overburden	Designates material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials or ores, especially those deposits that are mined from the surface by open cuts or open-pit methods.
Permeable Reactive Barrier	An emplacement of reactive materials in the subsurface designed to intercept a contaminant plume, provide a preferential flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals at points of compliance.
Pillar	A column of ore left to support the overlying strata or hanging wall in a mine, generally resulting in a "room and pillar" array. Pillars are normally left permanently to support the surface or to keep old workings water tight.
Pit Lake	A lake which has formed by accumulation of water in an open-pit mine excavation.
Pit Lake Water	Water which has filled an open-pit mine excavation, usually derived as water from underground workings of the mine.
Protore	Mineral bearing rock that cannot be further processed at a profit under existing conditions but that may become profitable with technological advances or price increases.

Pseudomorph	A mineral whose outward crystal form is that of, or which resembles another mineral species: it has developed by alteration, substitution, incrustation, or other mineral process.
Radiation Survey Radiological Survey)	Measurements of radiation levels associated with a site together (or with appropriate documentation and data evaluation.
Radioactivity	The mean number of nuclear transformations occurring in a given quantity of radioactive material per unit time. The International System (SI) unit of radioactivity is the Becquerel (Bq). The customary unit is the Curie (Ci).
Radioactive Decay	The spontaneous transformation of an unstable atom into one or more different nuclides accompanied by either the emission of energy and/or particles from the nucleus, nuclear capture or ejection of orbital electrons, or fission. Unstable atoms decay into a more stable state, eventually reaching a form that does not decay further or has a very long half-life.
Radionuclide	An unstable nuclide that undergoes radioactive decay.
Reclamation	Restoration of mined land to original contour, use or condition.
Reductant or Reduction	The addition of hydrogen, removal of oxygen, or addition of electrons to an element or compound.
Regulation	A rule, law, order, or direction from federal, state, or Tribal governments regulating action or conduct. Regulations concerning radionuclides in the environment in the United States are shared by the Environmental Protection Agency (EPA), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), state and Tribal governments.
Rem	Radiation Equivalent in Man. The conventional unit of dose equivalent. The corresponding International System (SI) unit is Sievert (Sv): 1 Sv = 100 rem.
Remediation	Cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a Superfund site, or uranium mine or extraction facility, including those included under the Uranium Mill Tailings Radiation Control Act (UMTRCA).

Refuse	Solid waste. Non-liquid, non-soluble materials ranging from municipal garbage to industrial wastes that contain complex and sometimes hazardous substances. Solid wastes also include sewage sludge, agricultural refuse, demolition wastes, mining equipment and mining residues. Technically, solid waste also refers to liquids and gases in containers.
Removal	The cleanup or removal of released hazardous substances, or pollutants or contaminants which may present an imminent and substantial danger; such actions as may be necessary taken in the event of the threat of release of hazardous substances into the environment; such actions as may be necessary to monitor, assess, and evaluate the threat of release of hazardous substances; the removal and disposal of material, or the taking of other such actions as may be necessary to prevent, minimize or mitigate damage to the public health or welfare or the environment.
Rill	A small channel, as one formed by erosion.
Risk Assessment	Qualitative and quantitative evaluation of the risk posed to human health and/or the environment by the actual or potential presence and/or use of specific pollutants.
Room and Pillar	A conventional method of underground mining in which natural pillars are left unmined for support between the mined rooms.
Rutile	A usually reddish-brown mineral (TiO_2) that is an ore of titanium.
Saturated Zone	A subsurface zone of soil or rock in which all the pore spaces are filled with water under pressure greater than that of the atmosphere. This zone is separated from the zone of aeration (above) by the water table.
Scanning	An evaluation technique performed by moving a detection device over a surface at a specified speed and distance above the surface to detect radiation.
Secular Equilibrium	A state of parent-daughter equilibrium that is achieved when the half-life of the parent radionuclide is much longer than the half-life of the daughter radionuclide decay product. In this case, if the two are not separated, the daughter will eventually decay at the same rate at which it is being produced. At this point, both parent and daughter will decay at the same rate until the parent is essentially exhausted.
Sievert (Sv)	The special name for the International System (SI) unit of dose equivalent. 1 Sv = 100 rem = 1 Joule per kilogram.
Site	Any mine or extraction facility installation, or discrete, physically separate parcel of land or lands disturbed by mining or uranium extraction, or any building or structure or portion thereof.
Soils	All unconsolidated materials above bedrock.

Solution Process	A method of extracting sought-after underground elements or minerals from in-place ore, or elements or minerals from ore previously mined and crushed. This is accomplished through the use of fluids which dissolve the mineral from the rock, putting it into liquid solution which is then processed or evaporated to obtain the desired element or mineral.
Solvent Extraction	A process for extracting a mineral or element (e.g., uranium) from ore by soaking rock with a (solvent) that dissolves the target element from the rock and putting it into liquid solution. The liquid is then processed or evaporated to obtain the desired element.
Source Materials	Uranium or thorium, or any combination thereof, in any physical or chemical form or (2) ores which contain by weight one-twentieth of one percent (0.05%) or more of: (i) Uranium, (ii) thorium or (iii) any combination thereof. Source material does not include special nuclear material. chemical
Special Nuclear Material	Plutonium, U-233, and Uranium enriched in U-235, material capable of undergoing a fission reaction.
Stewardship	Institutional controls (private or publicownership or governmental) which may be put in place to ensure that a specific site meets its closure goals. Institutional controls can be either active, involving some form of continuous or intermittent human activity to maintain the condition of the site, or passive, which do not require human intervention and have an amount of redundancy built into them to deter or prevent disturbance of the closed site.
Stope	An excavation from which ore has been removed in a series of steps. A variation of step. Usually applied to highly inclined or vertical veins or beds.
Survey	A systematic evaluation and documentation of radiological measurements with a correctly calibrated instrument or instruments that meet the sensitivity required by the objective of the evaluation.
Survey Plan	A plan for determining the radiological and other characteristics of a site.
TENORM	Acronym for Technologically Enhanced Naturally Occurring Radioactive Material. 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.
Underground Injection	The method by which fluids are placed under pressure in a well such that the fluid enters an underground rock formation. A means by which ISL wells inject lixiviant to dissolve uranium from underground ore bodies.
Unconsolidated	Rocks consisting of loosely coherent or uncemented particles, whether occurring at the surface or at depth.

Underflow	Flowing bottom waters containing dissolved or suspended solids.
Unsaturated zone	The zone in which the pore opening of the functional permeable rocks are not (except temporarily) filled with water under hydrostatic pressure; the interstices are either not filled with water or are filled with water that is held by capillarity.
Uprate	The process of increasing the maximum power level at which a commercial nuclear power plant may operate.
Volcaniclastic	A sedimentary rock containing volcanic material without regard to its origin or environment of deposition.
Waste Rock	Rock void of uranium ore which may have been set aside as waste after removal of top-soil, overburden and uranium ore or veins. Waste rock is defined as barren or submarginal rock or ore that has been mined, but is not of sufficient value to warrant treatment and is therefore removed ahead of the milling processes.
Wastewater	The spent or used water from a mine that contains dissolved or suspended matter.
Working Level	A special unit of radon exposure defined as any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy. This value is approximately equal to the alpha energy released from the decay of progeny in equilibrium with 100 pCi of Ra-222.

Appendix II. Uranium Decay Series

In the figures below, Figure AII.1. for the uranium-238 radioactive decay series, and Figure AII.2. for the uranium-23 radioactive decay series, each radioactive element is shown in a box with its mass number (^{226}Ra for example) along with its half life in μseconds (μsec), minutes (m), days (d), and years (y). The principal type of radiation given off as the radionuclide decays is shown alongside the box: alpha (α), beta (β).

Figure AII.1. Uranium–238 Radioactive Decay Series
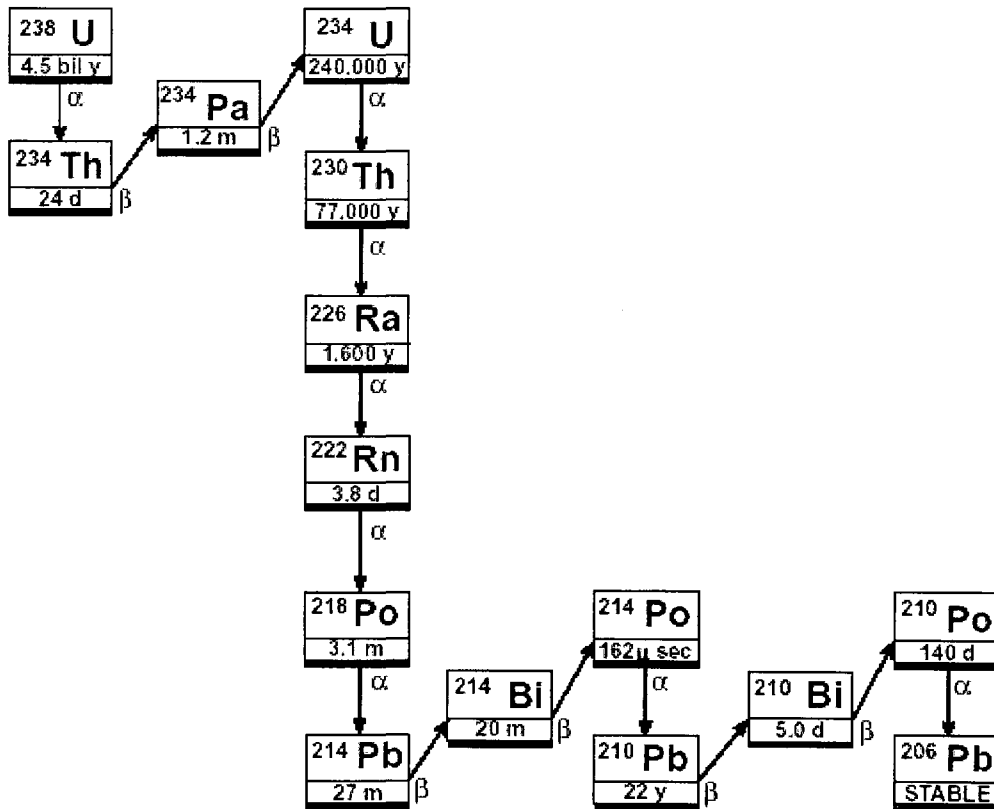
Figure AII.2. Uranium-235 (Actinium) Decay Series
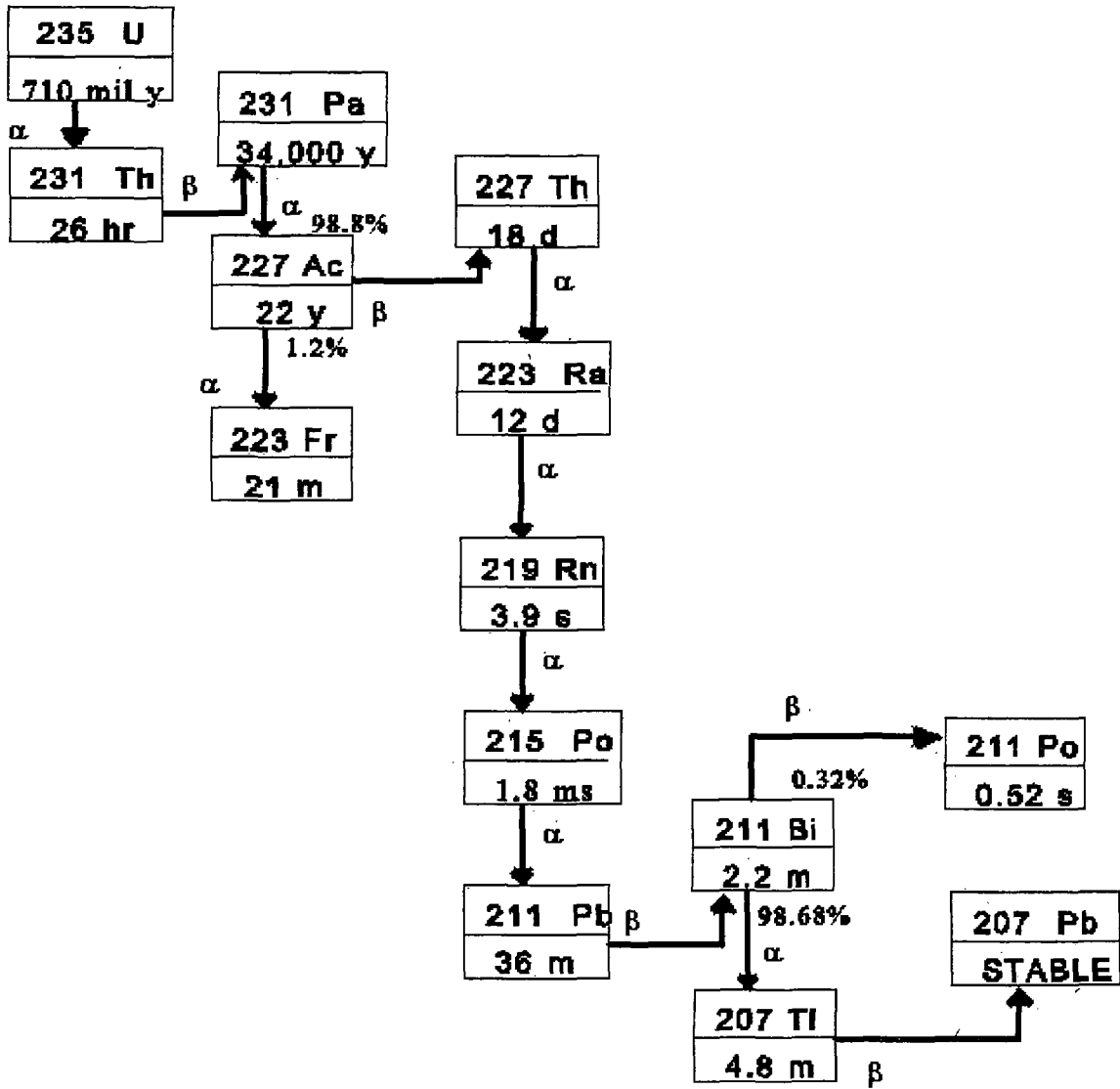
Appendix III. Overview of Uranium Mines and *In Situ* Leach Operations Case Studies

In the main body of this report, mention is made of a number of conventional uranium mines and ISL leach operations which were studied in detail by EPA in order to better understand the environmental conditions associated uranium extraction. Portions, though not all, of the data collected in the course of those studies were included in the report in order to illustrate points made in the text. The conventional mine sites listed in this appendix are abandoned, idle, or in reclamation status, and the descriptions which follow provide information on their location, size, and production status. ISL sites described were licensed facilities under the environmental oversight of and regulation of the NRC or its Agreement States. The wastes from those facilities are considered byproduct materials and not TENORM. As such, the information presented in this Appendix is for information purposes only. For a description of how new ISL operations are carried out, see Chapter 2.

A decision will be made in the near future about whether or not more detailed information on the conventional mine and ISL sites which was assembled as case studies for this report will be issued separately.

Canyonlands Uranium Mines, Lathrop Canyon, Utah

This is a group of 12 abandoned mines in sandstone deposits of southeastern Utah in a semi-arid region of the country. The mines are remotely located in Lathrop Canyon of the Canyonlands National Park near Moab, Utah, about 1½ hour hike from the nearest visitor's center at the park. Mine waste rock is found in piles inside and outside the mines, with contaminated water located below the mines. Contaminated water does not directly feed into any major bodies of water. Total waste amounts are estimated at 1,750 m³ (2,322 yd³). A study done by Burghardt et al. (2000) provides most of the data on the site contamination. Data are available on metals concentrations, pH, radiation levels, and electrical conductivity for the waste rock piles. Similar information is available for the Lathrop Canyon water and drainage. Based on this information, as well as population proximity information, the National Park Service and Utah Abandoned Mine Lands Reclamation Program maintain that Lathrop Canyon Mines now pose minimal risk to human safety and health.

Orphan Uranium Mine, Arizona

The Orphan Uranium mine is located at the Grand Canyon National Park in northern Arizona and is being assessed by the National Park Service for cleanup under CERCLA. The deposit is in sandstone and claystone, but occurs as a breccia pipe deposit. The mine's buildings, hoisting headframe, and ore loadout area are located a short walk from the south rim visitor's center, although the area has been fenced to deter visitors. Mining activities were conducted mainly between 1956 and 1969 for uranium, copper, silver, and vanadium. Radioactive rock and soil have been found at the loading area, and at the mine itself, which is located below the canyon rim. The mine still contains significant amounts of unmined uranium. Horn Creek, which lies beneath the Orphan Mine and along a major hiking trail of the park was found to discharge "hostile" effluent containing uranium and exceeding the maximum contaminant level for gross alpha radiation in drinking water. Uranium contamination of Horn Creek may be derived from: surface runoff from the upper mine site and tailing debris at the lower mine site; groundwater and surface water

that have percolated through the Orphan Mine, including the open glory hole; and ore and waste rock debris containing uranium that has eroded and has been swept into the drainage basin of Horn Creek. The case study includes results of Horn Spring sampling for uranium, as well as radiation levels recorded for the upper and lower mine sites. Approximately two million people visit the vicinity of the mine annually; however, relatively few individuals are directly exposed to radiation.

Further evaluation of the site in accordance with CERCLA is underway to evaluate the extent of contamination and cleanup alternatives. According to the National Park Service (U.S. NPS 2006), an Engineering Evaluation/Cost Analysis (EE/CA) should commence for the upper mine area in 2006. This study would analyze cleanup action and the effectiveness, feasibility, and cost of a number of cleanup alternatives. Upon completion, the EE/CA (including any recommended cleanup) and supporting documents would be made available to the public for review and comment. An EE/CA for the lower and middle mine areas was also being planned.

Midnite Uranium Mine, Washington

The Midnite Mine is an inactive open-pit uranium mine located within the boundaries of the Spokane Indian Reservation in eastern Washington State, and is a disseminated deposit in igneous rocks. It was operated by Dawn Mining Company between 1955 and 1981, and the disturbed area covers approximately 320 acres (129.6 hectares). The initial series of open-pits were backfilled with waste rock as mining progressed, and additional overburden and waste rock is on the surface, as well as a number of ore/protore stockpiles. Two large pits remain open and accumulate water from multiple sources, including seep water collected at the base of the largest waste rock pile. The pile was graded and partly reclaimed by the mining company, which also operates an ongoing seep collection system and $BaCl_2$ treatment facility. Midnite Mine was listed as a Superfund site in 2000, and an EPA-funded study is under way. In addition to the seeps and impounded surface water contaminated with heavy metals and radionuclides, contamination has spread to areas outside the mined area in surface water and sediments, groundwater, and road dust. Most runoff from the mined area flows to three streams (called "drainages"). The drainages meet south of the mine and flow into Blue Creek. Blue Creek travels an additional 3.5 miles to the Spokane River Arm of Lake Roosevelt. Shallow groundwater also flows from the mined area along the three drainages and emerges south of the mined area. Collection and treatment of contaminated water has reduced the amount of contamination entering surface water. However, the drainages and Blue Creek still show ongoing contamination from the mine. A proposed cleanup plan was issued by EPA in September of 2005.

Bluewater Uranium Mines, New Mexico

The Bluewater Uranium mines are a series of three sandstone mine sites located in north Central Cibola County in west-central New Mexico. Portions of the site had a semi-agricultural rural setting where approximately 65 persons lived in 1990. The mines were operated primarily between 1952 and 1966. Reclamation activities were conducted by EPA, ATSDR, and the Navajo Superfund Program to reduce potential radiological hazards associated with the mines. As a result of previous mining activities and the absence of reclamation action, the sites contained large open-pits with exposed uranium-bearing overburden, waste rock, and protore. A contaminated water well and houses constructed with uranium mine wastes were closed and removed. Radiological contaminants of concern were uranium and its

daughter products of radium, thorium, bismuth, lead, and radon gas. Heavy metal species suspected to be present in the mining waste were arsenic, barium, manganese, molybdenum, selenium, strontium, and vanadium, Analytical data on uranium and radium were collected prior to and after the completion of reclamation activities.

White King/Lucky Lass Uranium Mine Sites, Oregon

Also known as the Fremont National Forest Superfund Site, the site is located in south-central Oregon, and includes two former uranium mining areas encompassing about 140 acres (about 57 hectares). The site is located in a mountainous semi-arid setting on National Forest Service lands, with the closest residences and drinking water wells more than 10 miles (16 kilometers) from the site. The mines are located within the northwest terminus of the Basin and Range province. This area is characterized by north-trending fault-block mountains and basins of internal drainage. Geologic units in the region are characterized by a thick sequence of volcanic flows and volcaniclastic rocks which have been extensively faulted and fractured. The major features include a water-filled excavation pit (pond); a protore stockpile; an overburden stockpile; areas where overburden and ore were dumped or spilled; and Augur Creek, which flows adjacent to the two White King stockpiles. Mining operations were conducted between 1955 and 1965, with exploratory drilling conducted until 1979. The area has been extensively sampled for arsenic, uranium-234/238, radium, and radon. A baseline risk assessment was conducted and serves as part of the record of decision (ROD). Construction for remediation of the sites began in 2005.

Yazzie--312 Mine, Cameron, Arizona

The Yazzie-312 Uranium Mine is located on the Navajo Indian Reservation located in the Painted Desert section of the Black Mesa basin area near Cameron, Arizona. The site was operated between 1956 and 1961 and contained a large, water-filled open-pit lake; the water had been used for recreational swimming and livestock watering. The water standing in the Yazzie-312 pit was the result of an artesian flow from an underlying aquifer. The mine was in the Petrified Forest Member of the Chinle Formation. The mine operator drilled a hole in the bottom of the pit looking for a deeper ore horizon. The drill hole encountered artesian water in the Shinarump Member, which filled the pit.

The EPA studied the mine to determine: the presence of metals and radionuclides in water within the mine pit, in underlying water, and in the Little Colorado River; assessing metals and radionuclides in subsurface soil and sediments; determining infiltration in the water-filled mine pit; and assessing communication into other aquifers at the site. Analytical data were collected on several borings for soil samples, as well as several water samples. The area has several hard impermeable substrates located between 50 and 130 feet (15.2 and 39.6 meters) below ground surface. Elevated levels of uranium and thorium were found at soil depths that were above the groundwater table (110 to 210 feet) (33.5 to 64 meters-below ground surface), with significantly lower levels found at deeper depths. No metal levels exceeded EPA Region 9's Preliminary Remediation Goals. In the overburden and protore piles, the most significant contaminants were the uranium and thorium concentrations. Groundwater samples indicated contamination for uranium, radium, arsenic, beryllium, chromium, and manganese. Pit water tested similarly high for the same contaminants and for iron and lead. Testing also indicated that the Little Colorado River contained measureable uranium, arsenic, beryllium, and chromium, although not at significant levels. The mine site was remediated by the Navajo Abandoned Mine Land agency in 2002.

Uranium In Situ *Fields*

Crow Butte, Nebraska

Cameco's facility and associated wellfields are located in west-central Dawes County, Nebraska, just north of the Pine Ridge, five miles southeast of Crawford, Nebraska. The total surface area of the project site is approximately 2,800 acres (1,134 hectares), with about 500 acres (202 hectares) that will be disturbed during the life of the project. The uranium deposit at the Crow Butte site is a roll-front deposit, similar to those in the Wyoming basins. Liquid wastes from operations are generated from three sources: (1) wellfield development, (2) processing plant operations, and (3) aquifer restoration activities. Currently, Cameco has three options approved by the NRC for the disposal of liquid wastes: (1) solar evaporation ponds, (2) land application, or (3) deep-well injection. At this time, land application has not been used. The study contains results for lead, polonium, radium, radon, thorium, and uranium, taken from both the ponds located at the site and surface waters.

Holiday/El Mesquite, Texas

The Combined Holiday and El Mesquite ISL fields are located in Duval and Webb counties, Texas, and they cover a permit area of approximately 4,500 acres (1,822 hectares). They are owned by COGEMA which cited its total wellfield area as 335 acres (135 hectares) in two combined leases, with 1,750 injection wells and 1,450 production wells. Production commenced in 1977, with the expectation of 17 years of production and the fields' producing an ore grade of 0.07% using a sodium bicarbonate-injected lixiviant. Production from the fields averaged 750 tons of uranium per year, with an estimated extraction efficiency of 93 to 95%. Wastewater was collected at two storage ponds at the El Mesquite project before injection into deep disposal wells. The El Mesquite project lease area comprises 2,900 acres (1174 hectares) including five wellfields, three satellite locations, a processing plant, a yellowcake dryer, administrative buildings, a laboratory, a warehouse, and a maintenance shop. The Holiday lease covers 1,483 acres (600 hectares), including 10 wellfields and two satellite locations. Uranium production at the Holiday and El Mesquite project areas has ceased, and negative pressure in producing wells of the field is maintained to prevent excursions of pollutants (or plume migration) beyond mine lease boundaries. Areas that were depleted at an early point in the operations history were subjects of groundwater restoration activities. At Holiday and El Mesquite, the groundwater prior to extraction was usable for livestock watering, (with some localized exceptions, due to elevated radium-226, which is present in the groundwater within the uranium ore body). Therefore, COGEMA's goal after extraction is to clean up the groundwater to as close to background conditions as possible.

Irigaray and Christensen Ranch, Wyoming

The Irigaray and Christensen Ranch projects are two separate ISL operations that are located about 51 to 55 miles (82 to 88 kilometers) southeast of Buffalo in the Powder River Basin in northeast Wyoming. The Irigaray property is 21,100 acres (8,545 hectares) and contains the central plant for both projects, though the actual disturbed area for Irigaray is only 133 acres. COGEMA purchased both properties in April 1993, and all mining activities (at both sites) ceased in June 2000. The ore mineralization is one of many roll-front type uranium deposits located in the Wasatch formation. Water treatment processes, such as reverse osmosis, were used to clean wellfield bleed water for use in restoration. Uranium-laden resin from the ion exchange columns was transferred to a tanker trailer and trucked to the Irigaray central plant for elution, final uranium precipitation, and drying. Wastewater disposal capability included evaporation in lined ponds, storage of clean water (reverse osmosis permeate) in clay-lined ponds, treatment and disposal via surface discharge under a Wyoming National Pollutant Discharge Elimination System permit, and deep-well injection. The lined solar evaporation ponds were initially designed to provide a surface area and capacity capable of evaporating a 5 gallons per minute (about 19 liters per minute) process effluent stream. The four lined solar evaporation ponds were designed to meet the requirements of the NRC. Samples of the wastewater effluents were taken and tested for uranium and radium concentrations. Restoration of the Irigaray well fields was complete in August 2002 and was expected to be complete at Christensen Ranch in 2006. Surface decommissioning and reclamation are underway (as approved by NRC) and should be complete in 2007.

Crownpoint Uranium, New Mexico

The proposed Crownpoint Uranium ISL project consists of three properties located near Church Rock, New Mexico. Operations at the Crownpoint site would include a central processing facility where yellowcake will be dried and packaged. Generally, the uranium deposits are a few feet thick and several hundred to a thousand feet (305 meters) long, and may be stacked, usually parallel to the strike of the host rock. Uranium was proposed to be extracted from the ore bodies by leachate mining, using a sodium bicarbonate lixiviant, and is then extracted from the solution and concentrated. Uranium to be produced at the Church Rock and Unit 1 sites, uranium concentrate, in the form of either uranium-loaded resin beads or yellowcake slurry, would be shipped by truck to the central processing facility and packaged into a final yellowcake product. Before the waste would be disposed of, barium chloride would be added to effectively remove radium, thus lowering the radionuclide concentrations of the waste. HRI, the site's owner and operator, is currently considering up to five different final disposal options for wastewaters (both process-generated and restoration waters): (1) surface discharge, (2) land application, (3) brine concentration, (4) waste-retention ponds, and (5) deep-well disposal. At present, HRI is limited to using surface discharge (with appropriate state or federal permits/licenses), brine concentration, waste-retention ponds, or a combination of the three options to dispose of process wastewater. In July 2005, NRC required that HRI reduce its secondary groundwater restoration standard for uranium from 0.44 mg/L to 0.03 mg/L.

Highlands Uranium, Wyoming

Operated by Power Resources, Inc., Highlands is a 15,000-acre (6,073 hectare) ISL facility, located in the Southern Powder River Basin of east-central Wyoming, in central Converse County, Wyoming. The land has been used for seasonal sheep and cattle grazing. The uranium production process uses a lixiviant comprised of native groundwater with gaseous carbon dioxide and oxygen, which is injected into the ore zone through a series of well patterns. Uranium becomes dissolved within the lixiviant, which is pumped from the ground, treated to remove the uranium, then re-injected into the ore zone. Liquid wastes from the operation consist of two types of wastewater: (1) freshwater streams and (2) a saltwater stream. The freshwater streams consist of restoration wastewaters and well field/process purge. Together, the process purge and restoration fluids make up the irrigation water source. Power Resources disposes of its freshwater waste stream by using radium settling basins, purge storage reservoirs, and irrigation areas. Due to erosion problems encountered with the original clay liner of the ponds, a geotextile fabric was installed in September 1988 to protect against future erosion concerns. Data was obtained for radium and uranium in the settling ponds. Saltwater waste is disposed of in a waste disposal injection well. The saltwater waste is produced from several sources in the uranium recovery and yellowcake production process. The sources that make up this waste stream include analytical laboratory liquid wastes, elution agents decanted from the precipitation circuit, yellowcake wash water, reject solutions from the water treatment process, and washdown water from the Central Processing Facility.

Smith Ranch, Wyoming

This Power Resources project acquired from Rio Algom, is a 16,000-acre (6,480 hectare) site at the Smith Ranch, located in the North Platte River drainage in Converse County, approximately 17 miles (27.2 kilometers) northeast of Glenrock, Wyoming. Power Resources proposed to extract uranium at depths of 450 to 1,000 feet (137 to 305 meters). The project involves approximately 25 individual mining units. When the project was to be fully operational, about two years after licensing, approximately five mining units would be in production at a time. Extraction would proceed approximately three years in each unit, followed by an equivalent period of unit restoration and surveillance monitoring. The proposed schedule covers a total of about 20 years. Liquid effluents from the operation include the production bleed stream, excess fluids from the elution and precipitation process, regeneration of the water softener system (calcium control), yellowcake rinse water, plant washdown water, restoration equipment waste, restoration bleed, and facility sanitary waste. If the water quality was acceptable, the water would then be routed through a separate radium removal and solids settling system prior to evaporation and/or land application (surface irrigation). Excess liquids from the elution and precipitation circuit and water softener regeneration were expected to average about 60 gallons per minute (227 liters per minute) and would be routed to lined evaporation ponds or to a disposal injection well. In 2005, Power Resources applied for an amendment to the Smith Ranch/Highland license to include the adjacent planned Reynolds Ranch ISL project as a satellite facility. Sample data on radium and uranium concentrations in evaporation ponds from the pilot projects were obtained by EPA.

Appendix IV. Calculations of Volumes of Uranium Overburden and Waste Rock

Conventional mining techniques produce large amounts of solid waste materials. Open-pit mining in particular produces large quantities of overburden, while underground mining produces lesser, but still significant amounts of waste rock. Overburden and weakly mineralized waste rock that have not been used for reclamation have usually been stored in piles on site and are usually unsaturated, given that most conventional mining occurs in arid regions (U.S. DOE/EIA 1997). In general in this Appendix overburden and waste rock have been included together in estimating total waste rock at the mine sites.

The density of mine wastes varies, depending on the type of ore body with which they are associated and the geology of the enclosing rock formations. Standard weight per volume figures used in mine waste calculations are 1.68 tons/y^3 or 2 MT/m^3.

The approach used here is to estimate the ratio of waste rock production to ore production by mining category (open-pit and underground); calculate the amount of waste generated from annual production statistics (also given by mining category); and compare these numbers to waste volumes known or calculated for various mines.

When the uranium mining industry first started, most of the ores were recovered from deposits located at or near the surface. Ores were often exposed at the surface and shallow open-pit and underground mines often followed mineralized zones directly into the subsurface. The open-pit mines would remove thin overburden from buried parts of the ore body adjacent to the surface exposure. As easily accessible ore deposits became depleted, mining had to be performed at increasing depths by either open-pit or underground methods. In addition, lower grade ore deposits, once ignored, were later mined by using improved mining methods and more efficient ore extraction techniques. In the early mining years, an ore grade of 0.15% was often ignored; more recent mining practices target ore grades as low as 0.03%. Accordingly, over the years, the mining industry was required to move larger quantities of topsoil, overburden, and other waste rock in order to reach deeper deposits.

The amount of overburden that can be economically removed during open-pit mining is a complex function of the depth to the orebody, the grade and thickness of the ore-bearing zone, the price of uranium, and the costs of moving the overburden. The costs of processing ore at mills also influence the economics. Those processing costs, which apply to both underground and surface mines, have steadily declined and have lowered the ore grade that is economic to mine.

Information about the ratio of waste rock to ore can be derived from Abandoned Mine Land survey reports written since the mid-1980s, production statistics in files of the U.S. Geological Survey, from mining journal articles, from detailed descriptions of uranium mining operations in statewide compilations, and from interviews with mining engineers at selected properties. Such data are available for mines in Wyoming, Texas, Arizona, and New Mexico (Table AIV.1).

The ratio of waste rock to ore for mines of varying sizes shows that small open-pit mines are highly variable, but the ratios for the largest mines (greater than 900,000 MTs of ore) tend to range from 8:1 to 20:1. For example, the largest open-pit mine in the United States, the Jackpile-Paguate mine in New Mexico, was in the 12:1 range through the first 21 years of production (1953–73) but finished with an overall 16:1 ratio before production ceased in early 1982. The nearby St. Anthony open-pit mine had a stripping ratio of 10:1. The Shirley basin open-pit complex in Wyoming had an 8:1 waste to ore ratio.

Open-pits in Texas seem to have variable waste to ore ratios ranging from 2:1 to 20:1 for the smaller older pits on shallow ore bodies to relatively high values of 20:1 to 50:1 for the deeper deposits. Large open-pits dominate production in Wyoming and New Mexico, whereas smaller open-pits occur in Colorado, Utah, and Arizona. The Moonlight and Monument #2 open-pits in Arizona are thought to have had a 5:1 stripping ratio based on the depth to ore and ore thickness (Chenoweth 1998). Smaller open-pit operations in the range of 900 MTs to 900,000 MTs of ore have waste to ore ratios that generally range from 10:1 to 30:1.

The Jackpile-Paguate open-pit mine began production in 1953. Between 1953 and early 1963, 70 MMTs of overburden and associated waste and subore material had been removed to acquire 6.0 MMTs of ore (a ratio of about 11.8:1, Kittel 1963). By mid-1974, about 110 MMTs of overburden were removed and 9 MMTs of ore were recovered at an average grade of 0.25% (a 12:1 ratio, Graves 1974). Production ceased in early 1982, with a total of 364 MMTs of overburden and related materials removed from the ore body and 23 MMTs of ore produced (U.S. BLM 1986), a ratio of 16:1. The mine site contained 32 waste dumps and 23 protore dumps segregated according to grade. About 10.5 MMTs of protore were stored outside of the pits, and another 4.5 MMTs in dumps within pits. The ratio of all waste to protore was about 24:1. About 92 MMTs of backfill, comprised of ore-associated waste and some overburden, were returned to the pits during operations.

Throughout the 1950s, 1960s, and 1970s, open-pit mining was characterized by numerous small to moderate-sized open-pit operations with highly variable waste to ore ratios on the Colorado Plateau, by large open-pit mines in Wyoming and New Mexico with variable but usually lower waste to ore ratios, and by moderate to large open-pit operations in Texas with generally high waste to ore ratios. In the late 1970s and early 1980s waste to ore ratios for the largest mines appear to have peaked at an average of about 30:1 (Bohert and Gerity 1978; Facer et al. 1978). As the price of uranium dropped in the early 1980s, only the more efficient open-pit operations remained in production and the waste to ore ratios probably dropped significantly for the period 1984 to 1992.

Underground mining operations result in much smaller spoil storage piles than those generated by surface mines. Consequently, the waste to ore ratio generally ranges from 20:1 to 1:1 for underground mines, with an average ratio of about 9:1 (U.S. EPA 1983b). As with surface mining, this ratio has also increased over the years from a range of 5:1 until the early 1970s to about 1:1 by the late 1970s.

Table AIV.1 Waste to Ore Relation for Mines in Texas, Wyoming, Arizona, and New Mexico

State	Waste in tons	Ore in tons	Ratio
TX	37,300,000	1,945,366	19.2
	6,720,000	264,660	25.4
	2,040,000	52,390	38.9
	220,000	29,000	7.6
	138,600	7,899	17.5
	168,000	35,495	4.7
	5,980,000	117,709	50.8
	1,025,000	575,000	1.8
	1,610,000	117,775	13.7
	5,300,000	148,294	35.7
WY	121,106,000	14,687,480	8.2
	405,350,000	10,350,000	39.2
	69,050	10,900	6.3
	28,900	2,347	12.3
	25,200	1,000	25.2
	29,700	4,343	6.8
	7,728	201	38.4
	59,500	1,761	33.8
	15,900	256	62.1
	34,340	259	132.6
	6,540	67	97.6
	30,100	153	196.7
	42,700	54	790.7
	21,190	11	1926.4
	27,330	1,056	25.9
	9,160	358	25.6
	134,160	2,175	61.7
	3,440	61	56.4
	16,300	95	171.6
	72,996	2,341	31.2
	91,140	3,800	24.0
	154,812	4,000	38.7
	4,032	975	4.1
	25,450	22	1156.8
	10,350	63	164.3

Table AIV.1 Waste to Ore Relation for Mines in Texas, Wyoming, Arizona, and New Mexico (cont.)

State	Waste in tons	Ore in tons	Ratio
WY (cont.)	20,160	62	325.2
	7,190	7,130	1.0
	18,600	134	138.8
	37,800	1,270	29.8
	16,180	284	57.0
	22,390	1,345	16.6
	7,140	462	15.5
	18,300	1,471	12.4
	46,940	485	96.8
	3,090	387	8.0
AZ	758	3	252.7
	42,000	926	45.4
	202	7	28.8
	3,920	109	36.0
	61	6	10.1
	55,200	1,363	40.5
	706	123	5.7
	12,440	586	21.2
	4,200	305	13.8
	15,750	794	19.8
	958,220	33,821	28.3
	7,390	563	13.1
	226,800	1,264	179.4
	294,000	1,128	260.6
	19,320	218	88.6
	14,950	1,042	14.3
	2,100	23	91.3
	196,560	2,829	69.5
	22,340	343	65.1
	31,080	1,610	19.3
NM	364,000,000	23,000,000	15.8
	St. Anthony Pit		10.0
	50,000	10,400	4.8

Sources: *AVI 1986, HE 1987, RCT 1994, Kittel 1963, SRB 1981, Chenoweth 1998, McLenore 1983, Finch 1998.*

Uranium ore production rates since 1948 for conventional mining techniques and related production amounts of overburden are given in Table AIV.2. As shown in the table, the estimates for surface mine ratios (overburden to ore) are based on a factor of 30 for the entire period. This approach is believed to arrive at a total waste number for open-pit mines that seems reasonable (i.e. should not significantly over- or underestimate the number), considering the waste volumes associated with the largest mines (see discussion below).

For underground mines, a ratio of 3:1 was used for the years 1948–1970, and 1:1 was used for 1971 and later on. Despite the earlier EPA estimate mentioned previously, it is believed that applying a single ratio of 9:1 for all years would significantly underestimate the amount of waste generated during the last two decades.

Based on the preceding discussion, the total overburden produced by open-pit mines is estimated to range from 1 billion metric tons to 8 billion metric tons, with an average of 3 billion metric tons. For underground mines, the estimate ranges from 5 MMTs to 1 hundred MMTs, averaging 67 MMTs. Waste produced by open-pit mining is a factor of 45 greater than that for underground mining, based on their respective averages. For the range between the low and high estimates, the factor is 190 for the low estimate and 80 for the higher one. Thus, the amount of overburden generated from open-pit mines far exceeds that from underground mines.

The four largest mines in Table AIV.1 yield about 30% of the surface mine total; however, the size of mines drops dramatically as the rest of the inventory is considered. More than 1,000 of the 1,300 surface mines that have been operated in the past 50 years have produced less than 900 MTs of ore. These mines total less than 30-MMTs of waste, or less than 1% of the median estimate. Accordingly, the waste inventory produced by this industry is primarily the result of past operations at some 300 surface mines (SC&A 1989).

Table AIV.2. Uranium Ore Production Rates and Overburden 1948—1996

Year	Open-Pit Mining				Underground Mining			
	Ore (MTs)	Overburden (MTs)			Ore (MTs)	Overburden (MTs)		
		Low	Avg.	High		Low	Avg.	High
1948	<9.0E+02	9.1E+03	2.7E+04	7.3E+04	3.4E+04	1.7E+03	1.1E+04	3.4E+04
1949	9.1E+02	9.1E+03	2.7E+04	7.3E+04	1.6E+05	7.8E+03	5.2E+04	1.6E+05
1950	2.1E+04	2.1E+05	6.3E+05	1.7E+06	2.1E+05	1.0E+04	6.9E+04	2.1E+05
1951	2.5E+04	2.5E+05	7.6E+05	2.0E+06	2.9E+05	1.4E+04	9.6E+04	2.9E+05
1952	5.9E+04	5.9E+05	1.8E+06	4.7E+06	3.4E+05	1.7E+04	1.1E+05	3.4E+05
1953	1.6E+05	1.6E+06	4.9E+06	1.3E+07	5.0E+05	2.5E+04	1.7E+05	5.0E+05
1954	2.4E+05	2.4E+06	7.2E+06	1.9E+07	7.6E+05	3.8E+04	2.5E+05	7.6E+05
1955	3.4E+05	3.4E+06	1.0E+07	2.7E+07	1.0E+06	5.2E+04	3.5E+05	1.0E+06
1956	1.1E+06	1.1E+07	3.4E+07	9.1E+07	1.6E+06	8.0E+04	5.3E+05	1.6E+06
1957	1.5E+06	1.5E+07	4.4E+07	1.2E+08	1.9E+06	9.4E+04	6.3E+05	1.9E+06
1958	2.1E+06	2.1E+07	6.4E+07	1.7E+08	2.6E+06	1.3E+05	8.5E+05	2.6E+06
1959	2.0E+06	2.0E+07	6.0E+07	1.6E+08	4.3E+06	2.2E+05	1.4E+06	4.3E+06
1960	2.2E+06	2.2E+07	6.5E+07	1.7E+08	5.1E+06	2.5E+05	1.7E+06	5.1E+06
1961	2.3E+06	2.3E+07	6.8E+07	1.8E+08	5.0E+06	2.5E+05	1.7E+06	5.0E+06
1962	1.6E+06	1.6E+07	4.8E+07	1.3E+08	4.8E+06	2.4E+05	1.6E+06	4.8E+06
1963	1.7E+06	1.7E+07	5.1E+07	1.4E+08	3.7E+06	1.8E+05	1.2E+06	3.7E+06
1964	1.4E+06	1.4E+07	4.2E+07	1.1E+08	3.4E+06	1.7E+05	1.1E+06	3.4E+06
1965	1.1E+06	1.1E+07	3.4E+07	9.0E+07	2.8E+06	1.4E+05	9.5E+05	2.8E+06
1966	1.2E+06	1.2E+07	3.6E+07	9.7E+07	2.7E+06	1.4E+05	9.1E+05	2.7E+06
1967	1.4E+06	1.4E+07	4.3E+07	1.2E+08	3.4E+06	1.7E+05	1.1E+06	3.4E+06
1968	2.1E+06	2.1E+07	6.4E+07	1.7E+08	3.7E+06	1.9E+05	1.2E+06	3.7E+06
1969	2.0E+06	2.0E+07	5.9E+07	1.6E+08	3.4E+06	1.7E+05	1.1E+06	3.4E+06
1970	2.5E+06	2.5E+07	7.6E+07	2.0E+08	3.2E+06	1.6E+05	1.1E+06	3.2E+06
1971	3.0E+06	3.0E+07	8.9E+07	2.4E+08	2.7E+06	1.4E+05	2.7E+06	2.7E+06
1972	3.5E+06	3.5E+07	1.1E+08	2.8E+08	2.3E+06	1.1E+05	2.3E+06	2.3E+06
1973	4.1E+06	4.1E+07	1.2E+08	3.3E+08	1.8E+06	9.0E+04	1.8E+06	1.8E+06
1974	3.8E+06	3.8E+07	1.1E+08	3.1E+08	2.6E+06	1.3E+05	2.6E+06	2.6E+06
1975	3.9E+06	3.9E+07	1.2E+08	3.1E+08	2.5E+06	1.3E+05	2.5E+06	2.5E+06
1976	4.2E+06	4.2E+07	1.3E+08	3.4E+08	3.6E+06	1.8E+05	3.6E+06	3.6E+06
1977	5.1E+06	5.1E+07	1.5E+08	4.0E+08	4.3E+06	2.2E+05	4.3E+06	4.3E+06
1978	7.5E+06	7.5E+07	2.2E+08	6.0E+08	5.5E+06	2.8E+05	5.5E+06	5.5E+06
1979	8.8E+06	8.8E+07	2.6E+08	7.0E+08	4.9E+06	2.4E+05	4.9E+06	4.9E+06
1980	9.4E+06	9.4E+07	2.8E+08	7.5E+08	5.8E+06	2.9E+05	5.8E+06	5.8E+06
1981	7.7E+06	7.7E+07	2.3E+08	6.1E+08	4.7E+06	2.4E+05	4.7E+06	4.7E+06
1982	5.0E+06	5.0E+07	1.5E+08	4.0E+08	2.5E+06	1.3E+05	2.5E+06	2.5E+06
1983	4.4E+06	4.4E+07	1.3E+08	3.6E+08	2.3E+06	1.1E+05	2.3E+06	2.3E+06

Table AIV.2. Uranium Ore Production Rates and Overburden 1948—1996 (cont.)

Year	Open-Pit Mining				Underground Mining			
	Ore (MTs)	Overburden (MTs)			Ore (MTs)	Overburden (MTs)		
		Low	Avg.	High		Low	Avg.	High
1984	1.8E+06	1.8E+07	5.4E+07	1.4E+08	9.3E+05	4.7E+04	9.3E+05	9.3E+05
1985	8.5E+05	8.5E+06	2.5E+07	6.8E+07	5.2E+05	2.6E+04	5.2E+05	5.2E+05
1986	1.3E+05	1.3E+06	3.8E+06	1.0E+07	6.0E+05	3.0E+04	6.0E+05	6.0E+05
1987[a]	1.7E+05	1.7E+06	5.1E+06	1.4E+06	7.8E+05	3.9E+04	4.6E+05	4.6E+05
1988[a]	6.5E+05	6.5E+06	2.0E+07	5.2E+07	8.5E+05	4.3E+04	4.7E+05	4.7E+05
1989[a]	6.2E+05	6.2E+06	1.9E+07	5.0E+07	7.3E+05	3.7E+04	7.3E+05	7.3E+05
1990[a]	2.9E+05	2.9E+06	8.7E+06	2.3E+07	2.8E+05	1.4E+04	2.8E+05	2.8E+05
1991[a]	6.0E+05	6.0E+06	1.8E+07	4.8E+07	6.0E+05	3.0E+04	6.0E+05	6.0E+05
1992	<9.0E+02	--	--	--	<9.0E+02	--	--	--
1993	none	--	--	--	none	--	--	--
1994	none	--	--	--	none	--	--	--
1995	none	--	--	--	none	--	--	--
1996	none	--	--	--	<9.0E+02	--	--	--
Total	1.03E+08	1.03E+09	3.08E+09	8.21E+09	1.06E+08	5.29E+06	6.91E+7	1.06E+08
1948–1987		1.0E+09	3.0E+09	8.0E+09		5.2E+06	6.7E+07	1.0E+08
1987–1996		2.3E+07	6.7E+07	1.7E+08		1.6E+05	2.5E+06	2.5E+06

[a] Ore volumes not reported by mining category; volumes based on annual average uranium content of ore.

Appendix V. Radiochemical Data for Uranium Overburden and Waste Rock, Pit Lakes and Streams, and *In Situ* Leach Operations

Introduction

The following tables present radionuclide concentration data on solid and liquid wastes at conventional mines, pit lakes and streams, and from *in situ* leach operations. The data compiled has come from a wide variety of sources, many or most without uncertainty limits on the data provided. However, the information is instructive in providing a range of values for these wastes, from numerous mines and facilities throughout the west.

In several of the sources, measurements were reported for samples taken from conventional mine "waste" or "spoils" or "dumps" without distinguishing between overburden, soil, or waste rock, or potentially protore. Nevertheless, those studies provide a sense of how radioactive the wastes may be at those sites.

Table AV.1 Radiochemical, Exposure, and Radon Flux Data for Uranium Mine Waste

DataSource	Type of Data	U(nat) pCi/g[1] (Bq/g)	Ra-226 pCi/g[1] (Bq/g)	MicroR/hr	Radon Flux
AVI 1991	Avg. of 54 analyses	30.7 (1.14)	15.2 (0.56)		
Bullrush spoils, drill hole data	Range of 54 analyses	2–299 (0.07–3.7)	2–140 (0.07–5.18)		
Whitworth 1996	Mine waste, avg.	24.4 (0.9)	28.2 (1.04)		
La Bajada Mine, NM	Protore, avg.	75 (2.78)	613.5 (2.28)		
PEDCO 1983	Protore, NM	59 (2.18)	78.4 (0.259)		
	Protore	71.4 (2.64)	51.4 (1.9)		
	Protore	112 (4.14)	88.9 (3.29)		
	Protore	122 (4.51)	55.8 (2.06)		
	Protore	63.7 (2.36)	66.4 (2.46)		
	Waste	1.47 (0.05)	1.71 (0.06)		
	Waste	9.3 (0.34)	7.8 (0.29)		
	Waste	4.2 (0.16)	3.5 (0.13)		
	Waste	34.5 (12.77)	30 (1.11)		
	Protore, WY	8.55 (0.32)	37.4 (1.38)		
	Waste	17.6 (0.65)	1.17 (0.04)		
	Waste	1.35 (0.05)	10.8 (0.4)		
	Soil	0.51 (0.02)	0.71 (0.02)		
	Protore	129 (4.77)	82.2 (0.3)		
	Waste		1.23 (0.05)		
	Waste		0.81 (0.03)		
	Waste	0.61 (0.02)	3.2 (0.12)		
	Waste	1.17 (0.04)	1.06 (0.04)		
	Protore	54.4 (2.0)	67.9 (2.51)		

Table AV.1 Radiochemical, Exposure, and Radon Flux Data for Uranium Mine Waste (cont.)

DataSource	Type of Data	U(nat) pCi/g[1] (Bq/g)	Ra-226 pCi/g[1] (Bq/g)	MicroR/hr	Radon Flux
PEDCO 1983 (cont.)	Waste	0.93 (0.03)	2.15 (0.08)		
	Waste	0.18 (0.01)	2.74 (0.1)		
	Soil	1.55 (0.11)	1 (0.04)		
	Protore	97.1 (3.59)	148 (0.67)		
	Waste	7.1 (0.26)	5 (0.19)		
	Waste	4.9 (0.19)	6.3 (0.23)		
	Soil	4 (0.15)	3.9 (0.14)		
	Waste, μg	26.4	32.4		
	Waste, μg	5.8	6.1		
	Waste, μg	15.7	11.6		
	Waste, μg	24	16.4		
	Waste, μg	58.3	31.9		
	Waste, μg	58.7	39.4		
	Waste	6.2 (0.23)	4.4 (0.16)		
	Protore	137 (5.07)	118 (4.37)		
	Waste	30.5 (1.13)	25.8 0.95)		
	Protore	215 (7.96)	76.5 (2.83)		
	Waste	30.8 (1.14)	27.9 (1.03)		
	Waste	23.9 (0.88)	17.2 (0.04)		
	Waste, μg	54.3	40		
	Waste, μg	12.4	8		
EPA 1983	Boulder sites			40–100	
	Uravan			50–220	
	S.M., waste			35–275	
	ore			100–350	
	overburden			20–120	
	below ground			10–13	

AV-3

DataSource	Type of Data	U(nat) pCi/g[1] (Bq/g)	Ra-226 pCi/g[1] (Bq/g)	MicroR/hr	Radon Flux
EPA 1983 (cont.)	Mesa Top, waste			25–290	
	Barb Jo, waste			2–170	
	Poison C.,waste			65–250	
	overburden			25–65	
	Morton R., protore			200	
	overburden			59–138	
Burghardt 1998 Various surveys	Orphan (µg), AZ median			250	
	San Mateo (µg) spoils			10–450	
	San M., NM avg.			200	
	Lathrop mine (µg), waste			270–400	
				250	
				170–180	
		212 (7.84)	54 (2.0)		
		57 (2.11)	81 (3.0)		
		2.7 (0.1)	6.3 (0.23)		
		40 (1.48)	47 (1.74)		
	Muss		4.3 (0.16)		
			1.28 (0.05)		
			4.3 (0.16)		
	Jomac	163 (6.03)	110 (4.1)		
		35 (1.3)	206 (7.62)		
	Cath. Butte	17 (0.63)	25 (0.93)		
	Blue N.	7.3 (0.28)	8.5 (0.31)		
		22 (0.81)	26 (0.96)		
	W. Rk. Cn.	15.3 (0.57)	18 (0.67)		
		32 (0.67)	21 (0.78)		
	Terry	188 (6.96)	170 (6.29)		

Table AV.1 Radiochemical, Exposure, and Radon Flux Data for Uranium Mine Waste
(cont.)

DataSource	Type of Data	U(nat) pCi/g[1] (Bq/g)	Ra-226 pCi/g[1] (Bq/g)	MicroR/hr	Radon Flux
Burghardt 1998 Various surveys (cont.)		2.3 (0.09)	3.2 0.12)		
	Rainy Day	70 (2.59)	48 (1.78)		
		56.7 (2.1)	1.5 (0.06)		
		1.7 (0.06)	3.8 (0.14)		
		3.1 (0.11)	12 (0.44)		
Longsworth 1994	Monument Valley	Cameron area	AZ/UT		
	Moonlight Mine			18–22	
				43–630	
				185–320	
	Jeepster			18–23	
				19–20	
				5–20	
				47–150	
	Jack Daniels			70–190	
				35–220	
				27–85	
				33–75	
Moore et al. 1996	South spoil, drill hole avg.	85 ppm			
Midnite Mine, WA	Hillside spoil, drill hole avg.	82 ppm			
AVI 1986	Shirley Basin, WY				
	all piles, avg.		11.5 (0.43)		
LAI 1996	Rox ore pile, avg.			400	
	GV area, avg.			120	
	H&I, avg.			150	
	G spoils, avg.			150	
	Stan claims, avg.			500	
	B/R spoils, avg.			150	
	2States/Bl, avg.			250	
	Umetco, spoils, E			120	
	S			280	
	Sunset sp, avg.			200	
	max.			2,000	
	S-T spoils			50–150	
	Bullrush, avg.			90	
	P73 av			300	
	Classic/Bar protore			300–500	
	North Rex, avg.			40	

Table AV.1 Radiochemical, Exposure, and Radon Flux Data for Uranium Mine Waste (cont.)

DataSource	Type of Data	U(nat) pCi/g[1] (Bq/g)	Ra-226 pCi/g[1] (Bq/g)	MicroR/hr	Radon Flux
HE 1989	Pix-Veca pile, drill hole avg.		11.4 (0.42)		
	P-V, avg. 1,200 meas.			113 (4.2)	
	P-V surface avg.		27.2 (1.0)		
AVI 1990	Poison Basin-protore		55–140 (2.04–5.18)	250–600	
HE 1987	Pump Bts. Smpls	35 (1.3)	87 (3.22)	170	
		52 (1.92)	126 (0.44)	300	
		27 (1.0)	45 (1.67)	105	
		2.1 (0.08)	9 (0.33)	70	
	Jean-avg. ore piles			140	
	Key- below ground	22.1 (0.82)	12.7 (0.47)	40	
	waste	20.9 (0.77)	32.8 (1.21)	70	
	ore	688 (25.46)	185.6 (68.67)	300	
FPE 1988	Gas Hills-Jgpile, avg.		33.8		
	Jpile, avg.		15.5 (0.57)		
	Kpile, avg.		7.2 (0.27)		
WY AML Project 15	Converse County, WY				
	Avg. of 677,482 yds				
	of protore	170 ppm			
	Site II-avg.		51 (1.89)	74	30.7 (1.14)
	range		17–180 (0.63–6.67)	3.4-160	
	Average all drill hole in waste/protore piles 11 sites	93.6ppm	49.6 (1.84)		
RCT 1994	Range of 82 smpls of soil/spoil from 10 sites	<.85–668 ppm			

Table AV.1 Radiochemical, Exposure, and Radon Flux Data for Uranium Mine Waste (cont.)

DataSource	Type of Data	U(nat) pCi/g[1] (Bq/g)	Ra-226 pCi/g[1] (Bq/g)	MicroR/hr	Radon Flux
U.S. BLM 1986	Jackpile-Paguate, NM				
	Dump A waste	4.5 ppm		11 (0.41)	
	B waste	2.7 ppm		10 (0.37)	
	C waste	2.7 ppm		5 (0.19)	
	D waste	4.05 ppm		5 (0.19)	
	E waste	1.5 ppm		5 (0.19)	
	F waste	4.03 ppm		5 (0.19)	1.1 (0.04)
	G waste	5.82 ppm		5 (0.19)	4.15 (0.15)
	H waste	146.8 ppm		29 (1.07)	
	I waste	10.0 ppm		5 (0.19)	
	J waste	10.66 ppm		75 (2.78)	
	K waste	20.30 ppm		7 (0.26)	2.7 (0.10)
	L waste	5.5 ppm		5 (0.19)	2.57 (0.1)
	N waste	42.0 ppm		9 (0.33)	
	N2 waste	200.0 ppm		30 (1.11)	
	O, P, P1, P2 waste	3.12 ppm		12 (0.44)	
	Q waste	160.0 ppm		68 (2.52)	
	R waste	11.0 ppm		24 (0.89)	
	S waste	2.79 ppm		10 (0.37)	
	T waste	3.9 ppm		9 (0.33)	
	U waste	34.3 ppm		52 (1.92)	
	V waste	13.9 ppm		34 (1.26)	
	W waste	2.5 ppm		10 (0.37)	
	X waste	18.0 ppm		5	
	Y waste	33.4 ppm		13	

Table AV.1 Radiochemical, Exposure, and Radon Flux Data for Uranium Mine Waste (cont.)

DataSource	Type of Data	U(nat) pCi/g[1] (Bq/g)	Ra-226 pCi/g[1] (Bq/g)	MicroR/hr	Radon Flux
U.S. BLM 1986 (cont.)	Y2 waste	4.2 ppm		5	
	South waste	4.9 ppm		8	
	FD-1 waste	2.7 ppm		10	
	FD-2 waste	45.0 ppm		3	
	FD-3 waste	14.0 ppm		28	
	17BC protore	220.0 ppm		581	
	6A protore	200.0 ppm		388	
	6B protore	130.0 ppm		383	
	J1 protore	94.0 ppm		155	
	J2 protore	490.0 ppm		606	
	17D protore	520.0 ppm		198	
	1B protore	140.0 ppm		237	
	2C protore	110.0 ppm		422	
	10 protore	390.0 ppm		506	
	2D protore	180.0 ppm		419	
	1C protore	61.0 ppm		227	
	1A protore	31.0 ppm		161	
	2E protore	220.0 ppm		451	
	SP-1 protore	130.0 ppm		354	
	PLG protore	5.0 ppm		210	
	4-1 protore	77.0 ppm		266	
	SP-2 protore	180.0 ppm		300	
	SP-2B protore	610.0 ppm		164	
	TS-1 soil pile	4.9 ppm		8	
	TS-2A soil pile	4.9 ppm		18	
	TS-2B soil pile	2.9 ppm		6	
	TS-3 soil pile	3.6 ppm		11	
	Topsoil borrow	4.1 ppm		17	
Otton 1998	Ascensión mine	Front Range of CO			
	Waste/prot avg. 41 sites		45.7 (1.69)		
	Protore range		294–421 (10.88–15.58)	680–1,100	

Table AV.2 Radionuclide Concentrations in Ponds and Streams Associated with Open-pit Mines in Arizona, Texas, Utah and New Mexico

Data Source	Type of Data	U-238 ppb	U-235 pCi/L	Ra-226 pCi/L
Longsworth 1994	Monument Valley area, AZ–UT			
	Moonlight Mine—shallow well	11000	440 (1.63)	44 (1.63)
AZ-UT deposits	Moonlight Mine—shallow well	14000	530 (19.61)	110 (4.07)
	Moonlight Mine—pit water			8.6 (0.32)
	Radium Hill—drillhole water	210	12 (0.04)	19 (0.7)
	Radium Hill—shallow well	0.5	<0.1	0.16 (0.01)
	Cameron area, AZ			
	Jeepster Mine—pit water	22	0.8 (0.03)	0.25 (0.01)
	Jack Daniels Mine—ground water	150	5.7 (0.21)	0.1
	Jack Daniels Mine—pit water	11	0.4 (0.01)	0.07
	Manuel-Denetsone —drillhole water	180	8.9 (0.33)	0.52 (0.02)
	Ramco No. 20—small pit water	15	0.6 (0.02)	0.09
		U ppb		
RCT 1994 Texas mines.	Open-pit mine water samples			
	Stoeltje	600		
		700		
	Manka	250		
		200		
		300		
		220		
	I.M. Brysch	12		
		<1		
		14		
	Galen	<1		
	Butler	180		
		180		
		42		
		45		
		<1		
		<1		
		65		

Table AV.2 Radionuclide Concentrations in Ponds and Streams Associated with Open-pit Mines in Arizona, Texas, Utah and New Mexico (cont.)

Data Source	Type of Data	U-238 ppb	U-235 pCi/L	Ra-226 pCi/L
RCT 1994 Texas mines. (cont.)	Wright-McCrady	49		
		49		
	Esse	49		
		49		
	Sickenius	240		
		230		
	Kopplin	72		
		82		
	Smith	4,500		
		4,500		
	Pfeil	57		
		25		
	Weddington South	25		
		49		
	Kellner-Tenneco Weddington	220		
		170		
		200		
		300		
	Franklin	18		
		7		
U.S. BLM 1986	South Paguate—pit pond, N.M.			21.1 (0.78)
	North Paguate—pit pond			36 (1.33)
	South Jackpile—pit pond			18 (0.67)
	North Jackpile—pit pond			16.1 (0.60)
	Rio Paguate—upstream from mine	6		0.35 (0.01)
	Rio Moquino—upstream from mine	8		0.28 (0.01)
	Below confluence—down from mine	239		3.73 (0.14)
	Paguate Reservoir—down from mine	236		1.03 (0.04)

The following licensed ISL facilities are under the environmental oversight and regulation of the NRC and its Agreement States. The wastes from these facilities are considered byproduct materials and not TENORM. The information presented here is for information purposes only.

Table AV.3. In Situ Leach Operation Evaporation Pond Radionuclides, Crow Butte, Nebraska

Radionuclides	Pond Liquids (uCi/ml)
Lead-210	0.66×10^{-9}
Polonium-210	0.70×10^{-9}
Radium	0.65×10^{-9}
Radon	0.70×10^{-4}
Thorium-230	2.28×10^{-9}
Uranium	5.24×10^{-9}

Source: NRC License Application Supporting Materials.

Table AV.4.1 *In Situ* Leach Operation Evaporation Pond Radionuclides COGEMA, Irigaray Field, Wyoming

Sample Loc. /Date	Total U mg/L	Ra 226 pCi/L +/- Precision	Ra 226 Bq/L +/- Precision
IR-1 01/21/99	7.0	3.9/ 0.3	0.14/0.01
IR-1 04/16/99	18.3	8.1/0.5	0.30/0.02
IR-2A 01/21/99	15.1	46.3/1.9	1.71/0.07
IR-2A 04/16/99	1.90	68.9/2.4	2.55/0.9
IR-2B 01/21/99	6.0	29.1/1.5	1.08/0.07
IR-2B 04/16/99	3.96	50.5/2.0	1.87/0.07
IR-3 01/21/99	1.9	17.3/1.3	0.64/0.05
IR-3 04/16/99	0.746	8.4/0.5	0.31/0.02
IR-A 01/21/99	39.8	135/4.2	5.0/0.16
IR-A 04/16/99	36.0	151/4.7	5.59/0.17
IR-B 01/21/99	11.5	471/7.8	17.43/0.29
IR-B 04/16/99	11.8	439/7.9	16.24/0.29
IR-C 01/21/99	3.2	439/7.4	16.24/0.3
IR-C 04/16/99	3.0	325/5.4	12.03/0.2
IR-D 01/21/99	6.6	580/8.6	21.46/0.32
IR-D 04/16/99	6.0	529/6.6	19.57/0.24
IR-E 01/21/99	13.6	1,716/14.6	63.49/0.54
IR-E 04/16/99	13.4	1,760/12.3	65.12/0.46
IR-RA 01/21/99	3.0	16.9/1.2	0.63/0.04
IR-RA 04/16/99	31.0	39.0/1.9	1.44/0.07
IR-RB 01/21/99	46.5	5.1/0.4	0.19/0.01
IR-RB 04/16/99	86.0	11.5/1	0.43/0.04

Source: Quarterly Environmental Reports to the Nuclear Regulatory Commission.

Table AV.4.2. *In Situ* Leach Operation Evaporation Pond Radionuclides COGEMA, Christensen Ranch Field, Wyoming

Sample Loc. /Date	Total U	Ra 226 pCi/L	Ra 226 Bq/L
CR-1 01/21/99	8.6	107/2.9	3.96/0.11
CR-1 04/16/99	6.6	97.5/2.8	3.61/0.1
CR-2 01/21/99	1.10	1.5/0.2	0.06/0.01
CR-2 04/16/99	18.10	3.1/0.3	0.11/0.01
CR-3 01/21/99	0.443	1.4/0.2	0.05/0.007
CR-3 04/16/99	2.00	37.8/1.8	1.4/0.07
CR-4 01/21/99	0.07	1.5/0.2	0.06/0.007
CR-4 04/16/99	0.3160	23.7/1.4	0.88/0.05
CR-P1 01/21/99	0.021	0.8/0.2	0.03/0.007
CR-P1 04/16/99	0.0166	6.0/0.4	0.22/0.15

Source: Quarterly Environmental Reports to the Nuclear Regulatory Commission.

Table AV.5. *In Situ* **Leach Operation Evaporation Pond Radionuclides,**
Power Resources, Inc. Highlands Uranium Project, Wyoming

Purge Storage Reservoir PSR-1			Purge Storage Reservoir PSR-2		
	Ra-226			Ra-226,	
Date	pCi/L	Bq/L	Date	pCi/L	Bq/L
01/10/97	3.14	0.12	01/09/97	5.50	0.20
02/03/97	1.36	0.05	02/07/97	2.47	0.09
03/05/97	2.26	0.08	03/05/97	3.70	0.14
04/01/97	2.10	0.07	04/03/97	9.50	0.35
05/05/97	2.00	0.07	05/08/97	7.45	0.27
06/03/97	2.10	0.07	06/18/97	1.20	0.04
07/02/97	2.24	0.08	07/03/97	2.15	0.08
08/04/97	1.50	0.06	08/01/98	4.50	0.17
09/03/97	5.60	0.21	09/05/97	4.20	0.16
10/02/97	1.34	0.05	10/16/97	1.38	0.05
11/06/97	4.13	0.15	11/13/97	5.60	0.21
10/01/97	2.36	0.09	12/03/97	8.10	0.30
01/05/98	6.70	0.25	01/06/98	2.30	0.09
02/02/98	2.68	0.10	02/10/98	3.60	0.13
03/02/99	2.99	0.11	03/10/99	3.10	0.11
04/07/98	1.21	0.04	04/06/98	1.71	0.06
05/04/98	3.60	0.13	05/07/98	2.10	0.08
06/03/98	4.10	0.15	06/09/98	4.00	0.15

Source: Quarterly Environmental Reports to the Nuclear Regulatory Commission.

Table AV.5. *In Situ* **Leach Operation Evaporation Pond Radionuclides,
Power Resources, Inc. Highlands Uranium Project, Wyoming (cont.)**

E Radium Settling Basin					W Radium Settling Basin			
	U Total		Ra-226		U Total		Ra-226	
Date	pCi/L	Bq/L	pCi/L	Bq/L	pCi/L	Bq/L	pCi/L	Bq/L
03/20/97	4.60	0.17	1.30	0.05	5.30	0.20	8.30	0.31
06/30/97	3.00	0.11	5.10	0.19	3.00	0.11	5.10	0.19
09/03/97	2.26	0.08	8.00	0.30	2.18	0.08	1.20	0.04
12/30/97	5.96	0.22	7.00	0.26	4.29	0.16	1.10	0.04
03/24/98	4.80	0.18	1.20	0.04	3.61	0.13	2.80	0.10
06/22/98	4.85	0.18	1.30	0.05	2.26	0.08	9.00	0.33

Source: Quarterly Environmental Reports to the Nuclear Regulatory Commission.

Table AV.6. *In Situ* Leach Operation Evaporation Pond Radionuclides Rio Algom Mining Corp. (Now owned by Power Resources) Smith Ranch Project, Wyoming

Location Date	East Cell			West Cell		
	U mg/L	Ra226 pCi/L (Bq/L)	Th230 pCi/L (Bq/L)	U mg/L	Ra226 pCi/L (Bq/L)	Th230 pCi/L (Bq/L)
1st Qtr. 1982	1,100	2,378 (87.99)		16	172 (6.36)	
2nd Qtr. 1982	784	456 (16.88)		49	1,804 (66.75)	
3rd Qtr. 1982	38	100 (3.7)		132	2,119 (78.4)	
4th Qtr. 1982	275	315 (11.66)		131	1,779 (65.82)	
1st Qtr. 1983	4	86 (0.15)		2	22 (0.81)	
2nd Qtr. 1983	79	216 (0.96)		1	36 (1.33)	
3rd Qtr. 1983	13	108 (0.07)		14	44 (1.63)	
4th Qtr. 1983	103	483 (17.87)		100	553 (20.46)	
1st Qtr. 1984	22	42 (1.55)		1	34 (1.26)	
2nd Qtr. 1984	55	183 (6.77)		121	224 (8.29)	
3rd Qtr. 1984	105	21 (0.78)		105	7 (0.26)	
4th Qtr. 1984	141	5,095 (188.52)		--	--	
1st Qtr. 1985	12	3,030 (112.11)		--	--	
2nd Qtr. 1985	.20	643 (23.79)		.17	1,149 (42.51)	
3rd Qtr. 1985	.23	510 (18.87)		.23	490 (18.13)	
4th Qtr. 1985	.21	754 (27.90)		.22	552 (20.42)	
1st Qtr. 1986	.33	184 (6.8)		.14	423 (15.65)	
2nd Qtr. 1986	.25	1,366 (50.54)		.20	923 (34.15)	
3rd Qtr. 1986	.39	3,253 (120.36)		.38	2,081 (77.0)	
4th Qtr. 1986	.32	4 (0.15)		.27	41 (1.52)	
1st Qtr. 1987	.24	772 (2.86)		.25	755 (27.94)	
2nd Qtr. 1987	.25	1912 (70.74)		.23	560 (20.72)	
1st Half 1997	69.7	3,230 (119.51)	15.4 (0.57)	137	74.6 (2.76)	1.1 (0.04)
2nd Half 1997	27.8	57.1 (2.11)	0			
2nd Half 1999	92.4	945 (34.97)	6.2 (0.23)	70.8	203 (0.1)	0.7 (0.03)

Source: Quarterly Environmental Reports to the Nuclear Regulatory Commission.

The evaporation ponds were being sampled semiannually. Gamma radiation was measured quarterly at the evaporation ponds. The measurements obtained during the 1st & 2nd quarters of 1999 were 71 and 27 uR/hr, respectively.

Table AV.7. Evaporation Pond Leaks, Smith Ranch Project, Wyoming

Location	Date	U (nat) mg/L
East Pond	01/13/99	6.19
East Pond Stand Pipe	01/13/99	6.89
East Pond Stand Pipe	02/08/99	25.8
East Pond Sump	05/04/99	28
West Pond Sump	05/04/99	65
West Pond Sump	06/25/99	166
West Pond	10/23/99	75
West Pond Sump	10/23/99	193
West Pond Sump	10/29/99	150

Source: Quarterly Environmental Reports to the Nuclear Regulatory Commission.

Table AV.8. Deep-well Injection, Smith Ranch *In Situ* Leach Facility, Wyoming
The following is a table of the amounts and concentration of U Nat & Ra-226
disposed by UIC injection in 1998, 1999.

Date	Gals./month (liters/month)	Nat. Uranium mg/L *	Radium-226 pCi/L* (Bq/L)
June 1998		27.5	1,250 (46.25)
Sept. 1998		5.0	1,300 (48.10)
Dec. 1998		17.5	1,550 (57.35)
Jan. 1999	1,869,362 (7,076,095.9)		
Feb. 1999	1,832,431 (6,936,722.5)		
Mar. 1999	1,867,385 (7,068,612.4)	10.0	1,450 (53.65)
April 1999	1,906,162 (7,215,395.0)		
May 1999	1,952,301 (7,390,044.9)		
June 1999	1,713,467 (6,485,960.1)	19.0	1,050 (38.85)

* = *Values estimated from graph.*
Source: Quarterly Environmental Reports to the Nuclear Regulatory Commission.

Appendix VI. Legal Authorities Concerning Uranium, Uranium Mines and Extraction Facilities

Introduction

This section presents information on the authorities under which major federal, state and Tribal agencies operate. These authorities have been used to establish regulatory standards and requirements, and could potentially be used to develop additional guidances, or take other actions for the control of uranium TENORM, uranium mining, and uranium extraction facilities.

U.S. EPA

More than a dozen major statutes or laws form the legal basis for the programs of the EPA. EPA authority to develop radiation protection standards and to regulate radioactive materials including TENORM is derived from a number of those federal laws, plus Executive Orders.

The authority to develop Federal guidance for radiation protection was originally given to the Federal Radiation Council (FRC) by Executive Order in 1959 as an offshoot of authorities of the Atomic Energy Act (42 U.S.C. 2011 et seq.)(1954). Over the next decade the FRC developed federal guidance ranging from guidance for exposure of the general public, to estimates of fallout from nuclear weapons testing. Federal guidance developed by the FRC provided the basis for most regulation of radiation exposure by federal and state agencies, prior to the establishment of the EPA.

In 1970, the responsibility for developing Federal guidance for radiation protection was transferred from the FRC to the newly formed EPA under Executive Order 10831 and Reorganization Plan No. 3. Federal Guidance Documents are signed by the President and issued by EPA. By signing these, the President provides a framework for federal and state agencies to develop regulations that ensure the public is protected from the harmful effects of ionizing radiation. Federal Guidance is also an opportunity for the President to promote national consistency in radiation protection regulations. For example, the guidance document *Radiation Protection Guidance to Federal Agencies for Occupational Exposure*, issued by EPA in 52 CFR 2822 January 27, 1987, established general principles, and specifies the numerical primary guides for limiting worker exposure to radiation.

Clean Air Act (CAA)

EPA regulates radon and radioisotope emissions through its authority under the Clean Air Act (42 USC 7401 et seq.) (1970). Regulations promulgated by the Agency which control radioactive facilities and sites include 40 CFR 61:

- Subpart B, Underground Uranium Mines
- Subpart H, Department of Energy Facilities
- Subpart I, Certain non-DOE Facilities
- Subpart K, Elemental Phosphorous Plants
- Subpart R, Radon from Phosphogypsum Stacks
- Subpart W, Operating Uranium Mill Tailings

Under Subpart B, emissions of radon-222 to the ambient air from an underground uranium mine may not exceed amounts that would cause any member of the public to receive in any year an

effective dose equivalent of 10 mrem/y. Operators must provide a report to EPA annually on their compliance with the standard.

Under Subpart W, operating uranium mills must comply with the radon emission requirements of 20 pCi/(m2-sec)(1.9 pCi/(ft2-sec)) of radon-222, and other provisions under EPA's UMTRCA requirements in 40 CFR 192.32(a). Operators must provide a report to EPA annually on their compliance with the standard.

Under the Radon Gas and Indoor Air Quality Research Act (USC 42 et seq.)(1986) and Indoor Radon Abatement Act (1988), as well as authorities of the CAA, EPA has developed guidance for control of radon in homes, buildings and schools, and more recently for drinking water treatment and wastewater treatment facilities (U.S. EPA 2005, ISCORS 2005). The CAA gives EPA the authority to regulate emissions of both "conventional" pollutants, like PM_{10} (particulate matter less than 10 microns), and hazardous pollutants, such as radon. Both of these air pollutants are emitted by uranium extraction and beneficiation activities.

Clean Water Act (CWA)

The Clean Water Act's (33 USC 121 et seq., 1977) primary objective is to restore and maintain the integrity of the nation's waters. This objective translates into two fundamental national goals: eliminate the discharge of pollutants into the nation's waters, and achieve water quality levels that are fishable and swimmable. Under this law, EPA is given the authority to establish water quality standards and regulate the discharge of pollutants into waters of the United States, and this is performed under EPA's National Pollutant Discharge Elimination System-(NPDES). A point source is defined as any discrete conveyance, natural or man made, including pipes, ditches, and channels, and NPDES permits are issued by EPA or delegated States.

Section 502(6) of the CWA includes "radioactive materials" in the definition of pollutants. EPA's implementing regulations at 40·CFR 122.2, which defines the term "pollutants" includes radioactive materials except those regulated under the AEA. The law also gives EPA the authority to regulate, through permits, storm water discharges from both inactive and active mine sites. Mines and mills that discharge must obtain a permit, and must monitor twice a year for specific pollutants determined by the type of ore they mine or process. EPA regulations in 40 CFR 440, Part C, are applicable to discharges from (a) mines either open-pit or underground (ISL operations are excluded), from which uranium, radium and vanadium ores are produced; and (b) mills using the acid leach, alkaline leach, or combined acid and alkaline leach process for the extraction of uranium, radium and vanadium.

These regulations provide effluent limitations based upon best practicable control technology (BPT) and best achievable technology (BAT) for uranium mills and open-pit and underground uranium mines, including mines using ISL methods. Discharges from regulated operations must meet best available technology/best practicable technology (BAT/BPCT) standards for zinc, arsenic, ammonia, dissolved radium-226, total radium, uranium, total suspended solids (TSS), chemical oxygen demand (COD), and pH. A summary of the standards is included in Chapter 1, as well as in more detail in U.S. EPA (1995a), and 40 CFR 440 Subpart C: 440.32, 440.33, and 440.34. Individual states are required to adopt water quality criteria at least as stringent as federal levels. The application of these criteria is based on the designated use of a specific receiving water (drinking water supply, aquatic life, and/or recreational use).

Except as provided in cases of unusually high storm water events, EPA has regulated that there shall be no discharge of process wastewater to navigable waters from mills using the acid leach, alkaline leach or combined acid and alkaline leach process for the extraction of uranium or from mines and mills using ISL methods. The only exception occurs if annual precipitation falling on the treatment facility and the drainage area contributing surface runoff to the mine or mill's water treatment facility exceeds the annual evaporation. In such cases, the volume of water exceeding annual evaporation may be discharged subject to the numerical limitations for uranium and radium discharge mentioned above.

Some discharges from mine sites do not meet the definition of a "point source discharge." These discharges are nonpoint source discharges. Under Section 319 of the CWA, States are required to prepare nonpoint source assessment reports and to develop programs to address nonpoint sources, including active and inactive/abandoned mine sites, on a watershed-by-watershed basis. Each state must report to EPA annually on program implementation and resulting water quality improvements.

Safe Drinking Water Act (SDWA)

The Safe Drinking Water Act (42 USC 300f et seq., 1974), is the main federal law that ensures the quality of Americans' drinking water. Under the SDWA, EPA sets standards for drinking water quality and oversees the states, localities, and water suppliers who implement those standards. Implementing regulations for 40 CFR 141 include the establishment of national primary drinking water standards which currently include maximum contaminant level goals and maximum contaminant levels (MCLs) for radiation and radionuclides. The standards also include combined Ra-226 and Ra-228, Uranium, gross alpha excluding uranium and radon, man-made beta and photon emitters. A draft MCL has also been proposed for Radon. EPA established a UIC program under the authority of the SDWA. Through this program, the Agency has a permit system to ensure underground sources of drinking water are protected from the injection of process fluids and liquid wastes, including those produced during uranium extraction and beneficiation, into the subsurface via wells.

EPA's UIC regulations protect underground sources of drinking water (USDWs) by prohibiting the direct injection or migration of foreign fluids into these aquifers. A USDW is defined as any aquifer or its portion that supplies a public water system or contains fewer than 10,000 mg/l total dissolved solids (TDS). An aquifer may be exempted from UIC regulation if it is shown to be completely isolated with no possible future uses. In general, federal regulations prohibit any underground injection unless authorized by permit or by rule. In addition, no owner/operator of a well may construct, operate, maintain, convert, plug, or abandon an injection well in a manner which allows the movement of contaminated fluid into underground sources of drinking water. The program establishes requirements for five injection well categories. Regulations vary according to the class of well. These categories are outlined below:

Class I: Injection wells for hazardous, industrial, non-hazardous, and municipal wastewater disposal below the lower most formation, within 1/4 mile of the wellbore, containing an underground source of groundwater.

Class II: Injection wells for fluids related to oil and gas production such as salt water disposal wells, enhanced oil recovery wells and hydrocarbon storage wells.

Class III: Injection wells related to mineral extraction such as ISL production of uranium, only for ore bodies which have not been conventionally mined.

Class IV: Disposal of radioactive or hazardous waste into or above a formation which contains an underground source of drinking water within 1/4 mile. Section 3020(a) of RCRA prohibits the construction and operation of Class IV wells.

Class V: Injection wells not included in the other classes. This includes solution mining of conventional mines, such as isotope leaching and low-level radioactive waste wells.

Classes I, III and V are potentially applicable to the uranium extraction and beneficiation industry. Enforcement of the requirements of the SDWA may be delegated by EPA to states. Under the regulations, EPA may permit injection wells for uranium ISL operations. EPA's regulations issued under UMTRCA authority provide the principal standards for uranium ISL operations and groundwater protection, while the UIC regulations are considered additional requirements for ISL operations. Under UIC permits, the Agency usually exempts that portion of an aquifer constituting the well field from meeting drinking water standards. However, under EPA standards established under UMTRCA authority, the operator of the ISL restores the well field to either background conditions or EPA drinking water maximum contaminant limit levels where possible or practical. When this can not be accomplished, Alternate Concentration Limits (ACLs), 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.

CERCLA (Superfund)

The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) (42 USC 9601 et seq.,1980) and the Superfund Amendments and Reauthorization Act (SARA) (42 USC 9601 et seq., 1986) provided broad Federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment. CERCLA established prohibitions and requirements concerning closed and abandoned hazardous waste sites; provided for liability of persons responsible for releases of hazardous waste at these sites; and established a trust fund to provide for cleanup when no responsible party could be identified. EPA has determined that radiation is a carcinogen and thus a hazardous substance. Under the National Oil and Hazardous Substances Contingency Plan (NCP), EPA has issued guidance on removals and cleanup of radioactively contaminated sites, including those contaminated with the TENORM radionuclides radium, thorium and uranium. Implementing regulations for the NCP are found at 40 CFR 300.

The Toxic Substances Control Act (TSCA)

The Toxic Substances Control Act (TSCA) (15 USC 2601 et seq., 1976) was enacted by Congress to give EPA the ability to track the 75,000 industrial chemicals currently produced or imported into the United States. EPA repeatedly screens these chemicals and can require reporting or testing of those that may pose an environmental or human health hazard. EPA can ban the manufacture and import of those chemicals that pose an unreasonable risk. While radionuclides are considered toxic substances under the Act, source material, special nuclear material, or byproduct material (as such terms are defined in the AEA, and regulations issued under such Act) are excluded from coverage. Consequently, TENORM radionuclides may be subject to this law, though EPA has not previously applied it in this way.

The Resource Conservation and Recovery Act (RCRA)

The Resource Conservation and Recovery Act (RCRA) (42 USC 321 et seq., 1976) gave EPA the authority to control hazardous waste. This includes the generation, transportation, treatment, storage, and disposal of hazardous waste. RCRA also set forth a framework for the management of non-hazardous wastes. The 1986 amendments to RCRA enabled EPA to address environmental problems that could result from underground tanks storing petroleum and other hazardous substances. RCRA focuses only on active and future facilities and does not address abandoned or historical sites (see CERCLA). HSWA (the Federal Hazardous and Solid Waste Amendments) are the 1984 amendments to RCRA that required phasing out land disposal of hazardous waste. Some of the other mandates of this strict law include increased enforcement authority for EPA, more stringent hazardous waste management standards, and a comprehensive underground storage tank program. EPA's implementing regulations for RCRA do not address disposal of radioactively contaminated substances in landfills, however nuclear accelerator wastes (a form of waste previously classified as part of the TENORM waste class) has been disposed of in such facilities, depending on the permitting authority.

Uranium Mill Tailings Radiation Control Act (UMTRCA)

EPA does not license uranium mills or ISL facilities. However, it does establish certain environmental standards which must be adopted by the NRC and its Agreement States and DOE for uranium processing facilities. Current regulations applicable to remediation of both inactive uranium mill tailings and uranium extraction facilities, including vicinity properties and ISL operations, active uranium and thorium mills, and ISL operations, have been issued by the EPA under the Uranium Mill Tailings Radiation Control Act (UMTRCA) (42 USC 2022 et seq.) of 1978, as amended. EPA's regulations in 40 CFR 192 apply to remediation of such properties and address emissions of radon, as well as radionuclides, metals, and other contaminants into surface and groundwater.

Under UMTRCA, EPA has the responsibility to establish standards for exposure of the public to radioactive materials originating from mill tailings, and for cleanup and control standards for inactive uranium processing sites and associated vicinity areas, as well as for active uranium extraction facilities licensed by the NRC or its Agreement States. To the maximum extent possible, those standards were required to reflect the requirements issued by EPA under the Solid Waste Disposal Act (now RCRA), and do so by referencing 30 CFR Part 261 regulations.

Tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content is defined by Section 11e.(2) of the Atomic Energy Act as byproduct material. That material is not considered to be TENORM in the U.S., and is regulated by the NRC or its Agreement States. Under UMTRCA, the NRC must utilize EPA environmental protection standards to develop its regulations for active and inactive uranium milling and extraction facilities. The NRC does not have regulatory authority over conventional type uranium mine wastes (see NRC discussion below).

U.S. Nuclear Regulatory Commission

The mission of the NRC is to ensure adequate protection of the public health and safety, the common defense and security, and the environment in the use of nuclear materials in the United States. The NRC's scope of responsibility includes regulation of commercial nuclear power reactors; research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials and waste.

The NRC was created as an independent agency by the Energy Reorganization Act of 1974, which abolished the AEC and moved the AEC's regulatory function to NRC. This act provides the foundation for regulation of the nation's commercial nuclear power industry.

NRC regulations are issued under the United States Code of Federal Regulations (CFR) Title 10, Chapter 1. Principal statutory authorities that govern NRC's work are:

- Atomic Energy Act of 1954, as amended
- Energy Reorganization Act of 1974, as amended
- Uranium Mill Tailings Radiation Control Act of 1978, as amended
- Nuclear Non-Proliferation Act of 1978
- Low-Level Radioactive Waste Policy Act of 1980
- West Valley Demonstration Project Act of 1980
- Nuclear Waste Policy Act of 1982
- Low-Level Radioactive Waste Policy Amendments Act of 1985
- Diplomatic Security and Anti-Terrorism Act of 1986
- Nuclear Waste Policy Amendments Act of 1987
- Solar, Wind, Waste and Geothermal Power Production Incentives Act of 1990
- Energy Policy Act of 1992

The NRC and its licensees share a common responsibility to protect the public health and safety. Federal regulations and the NRC regulatory program are important elements in the protection of the public. NRC licensees, however, have the primary responsibility for the safe use of nuclear materials.

The NRC fulfills its responsibilities through a system of licensing and regulatory activities that include:

1) Licensing the construction and operation of nuclear reactors and other nuclear facilities, such as nuclear fuel cycle facilities and test and research reactors, and overseeing their decommissioning;
2) Licensing the possession, use, processing, handling, and export of nuclear material;
3) Licensing the siting, design, construction, operation, and closure of low-level radioactive waste disposal sites under NRC jurisdiction and the construction, operation, and closure of the geologic repository for high-level radioactive waste;
4) Licensing the operators of nuclear power and non-power test and research reactors; inspecting licensed facilities and activities;
5) Conducting the principal U.S. Government research program on light-water reactor safety;
6) Conducting research to provide independent expertise and information for making timely regulatory judgments and for anticipating problems of potential safety significance;

7) Developing and implementing rules and regulations that govern licensed nuclear activities;

8) Investigating nuclear incidents and allegations concerning any matter regulated by the NRC;

9) Enforcing NRC regulations and the conditions of NRC licenses;

10) Conducting public hearings on matters of nuclear and radiological safety, environmental concern, common defense and security, and antitrust matters;

11) Developing effective working relationships with the States regarding reactor operations and the regulation of nuclear material;

12) Maintaining the NRC Incident Response Program, including the NRC Operations Center; and

13) Collecting, analyzing, and disseminating information about the operational safety of commercial nuclear power reactors and certain non-reactor activities.

Atomic Energy Act – Regulation of Source Material

Under the AEA, the AEC, now the NRC, was given responsibility for regulation of "source material". Source material includes either the element thorium or the element uranium, provided that the uranium has not been enriched in U-235. Source material also includes any combination of thorium and uranium, in any physical or chemical form, or ores that contain by weight 0.05 percent or more of uranium, thorium, or any combination thereof. Depleted uranium (left over from uranium enrichment) is considered source material. Source material can result from the milling and concentration of uranium contained in ore mined for its uranium content. As the chemical refining processes are generally the same, the NRC also regulates source material generated from ISL operations. It can also be generated in the process of refining ores mined for other precious metals. In addition, source material can arise from the reprocessing of spent nuclear fuel (no commercial reprocessing is currently licensed in the U.S.) and also, as depleted uranium (contains lower levels of U-235 than natural uranium), from the process of enriching uranium in the isotope U-235. However, the NRC does not regulate conventional (open-pit and underground) mining of uranium or thorium ore. NRC's regulations for source material facility licensing are found at 10 CFR 40.

Guidance for applications for ISL operation licenses are contained in NUREG 1569 (U.S. NRC 2003). An applicant for a new operating license, or for the renewal or amendment of an existing license, is required to provide detailed information on the facilities, equipment, and procedures to be used and to submit an environmental report that discusses the effect of proposed operations on public health and safety and the impact on the environment. This information is used by NRC staff to determine whether the proposed activities will be protective of public health and safety and will be environmentally acceptable.

Regulations in 10 CFR Part 51, provide for environmental protection regulations for domestic licensing and related regulatory functions, while those in 10 CFR Part 20 cover radiation protection standards. Fuel cycle facility inspections which enforce these regulations focus on the areas that are most important to safety and safeguards, using objective measures of performance called "performance indicators." Inspections at fuel cycle facilities occur several times a year and typically cover activities such as chemical process, emergency preparedness, fire safety, and radiation safety. Uranium mill facilities in standby status (non-operational) are inspected every three years. Also, specialized inspections are conducted using personnel from NRC headquarters in Maryland and the Region II office in Atlanta, Georgia. Inspectors follow guidance in the NRC Inspection Manual that contains objectives and procedures to use for each type of inspection. The inspection program for fuel cycle facilities is being revised to accommodate the use of risk

insights to focus the NRC and its licensees on matters that are most important to safety and safeguards.

Atomic Energy Act-- Regulation of Byproduct Material

Section 11e.(2) byproduct material, as defined by the AEA, is regulated by the NRC under 10 CFR Part 40. In Part 40, the NRC clarified the definition of byproduct material by adding the clause "including discrete surface wastes resulting from uranium solution extraction processes." In simpler terms, it is the waste and tailings generated by the processing of ore for its uranium or thorium content. Most of this material is created by uranium milling and is primarily mill tailings. Examples of milling wastes are broken pipe from ISL facilities and contaminated mill equipment that is to be discarded. Byproduct material from uranium mining and milling is disposed of in uranium mill tailings impoundments.

Under the Energy Policy Act of 2005, the Atomic Energy Act was amended to place additional "discrete sources of naturally occurring radioactive material" under NRC jurisdiction. The primary focus of this provision is on security and the potential misuse of such materials. This suggests that the materials of concern will be those that are highly radioactive in small quantities, though "discrete" in this context will be defined further after consultation between NRC and the EPA, and the states, as well as through the regulatory process. These wastes are not those resulting from uranium or thorium processing.

The definition of byproduct materials was modified by the Act to include: "Any discrete source of Ra-226 that is produced, extracted or converted after extraction, before, on or after the date of enactment of this paragraph *(August 8, 2005)* for use for a commercial, medical, or research activity, or (B) any material that (i) has been made radioactive by use of a particle accelerator, and (ii) is produced, extracted, or converted after extraction, before, on, or after the date of enactment of this paragraph for use for a commercial, medical or research activity;
    and
any discrete source of naturally occurring radioactive material, other than source material, that: (A) the Commission, in consultation with the Administrator of the Environmental Protection Agency, the Secretary of Energy, the Secretary of Homeland Security, and the head of any other appropriate Federal agency, determines would pose a threat similar to the threat posed by a discrete source of radium-226 to the public health and safety or the common defense and security, and (B) before, on, or after the date of enactment of this paragraph *(August 8, 2005)* is extracted, or converted after extraction for use in a commercial, medical or research activity."

Waste disposal for this new class of byproduct material must be in a disposal facility that: (a) is adequate to protect public health and safety, and (b)(i) is licensed by the Commission; or(ii) is licensed by a state that has entered into an agreement with the Commission under section, if the licensing requirements of the state are compatible with the licensing requirements of the Commission. The Act also included provisions to allow disposal in a non-NRC licensed facility.

States with Agreement State status can receive authority over byproduct material. However, in states without Agreement State status, the NRC retains authority over byproduct material.

Uranium Mill Tailings Radiation Control Act

The U.S. Government began to purchase uranium for defense purposes in the early 1940's. Since that time, large quantities of tailings have been generated by the uranium milling industry. In many cases, these tailings were dispersed from impoundments and piles by natural forces and by humans for construction use in or around buildings, or for roads. UMTRCA, which in 1978 amended the AEA, established two programs to protect the public health, safety and the environment from uranium mill tailings.

Title I of UMTRCA addresses 22 Congressionally designated sites (to which DOE added 2 more) that were inactive (e.g., all milling had stopped and the site was not licensed by the NRC). Title II of UMTRCA addresses active sites (those with NRC or Agreement State licenses) (48 FR 45926). UMTRCA requires the NRC to concur with remedies DOE selects for cleaning up and controlling inactive sites. Under UMTRCA, the NRC is also responsible for licensing inactive uranium tailings sites that have undergone remediation. Inspection, reporting, and record-keeping requirements are defined in 10 CFR 40.27 under which mill tailings impoundment and some adjoining land will be turned over to the DOE, another federal agency designated by the President, or the state in which the site is located for long-term care. License termination usually involves a confirmation that all applicable reclamation requirements have been met. This includes ensuring completion of stabilization work for the tailings consistent with the accepted reclamation plan and a determination that the licensee has complied with all standards applicable to land structures, and groundwater cleanup.

U.S. Department of Energy

In the 1970s, the Atomic Energy Commission was abolished and the Energy Reorganization Act of 1974 (42 USC. Sec. 5813, 5817, et seq.) created two new agencies: the Nuclear Regulatory Commission to regulate the nuclear power industry and the Energy Research and Development Administration to manage the nuclear weapon, naval reactor, and energy development programs. However, the extended energy crisis of the 1970s soon demonstrated the need for unified energy organization and planning. The Department of Energy Organization Act (42 USC Sec. 5916, 7112, et seq.) brought the Federal Government's energy agencies and programs into a single agency. Established on October 1, 1977, the Department of Energy assumed the responsibilities of the Federal Energy Administration, the Energy Research and Development Administration, and parts and programs from several other agencies.

The Department of Energy's overarching mission is to advance the national, economic and energy security of the United States; to promote scientific and technological innovation in support of that mission; and to ensure the environmental cleanup of the national nuclear weapons complex.

Uranium Mill Tailings Radiation Control Act

Principal responsibility for management of uranium mill tailings facilities under UMTRCA is handled by DOE's Office of Legacy Management. The office's primary functions include: management of the land and associated resources as a federal trustee, surveillance and maintenance associated with environmental remedies, records and information management, and the management of post-closure liabilities. Sites transferred to the Office include UMTRCA sites, where remediation is complete. As more sites are successfully remediated and closed, the site

surveillance and maintenance functions, and worker benefits as appropriate, will be transferred for long-term management.

For UMTRCA Title I disposal sites managed by the Office, DOE becomes a licensee to the NRC. The general license for long-term custody is indefinite in duration, and the land is administratively withdrawn from unrestricted public use. Sites located on Tribal land revert to Tribal control, and DOE obtains a site access agreement with the Tribe that allows DOE to fulfill its custodial responsibilities.

Title I of UMTRCA provided for the remediation and reclamation of 24 uranium mill processing sites and approximately 5,200 associated vicinity properties by the DOE. Remediation of these sites under DOE's UMTRA resulted in the creation of disposal cells that contain encapsulated uranium mill tailings and associated contaminated material. The stated goals of the UMTRA Program were to: (1) address immediate risk concerns and prevent further increases in relative risk at all sites; (2) complete surface remedial action work at all 24 mill tailings sites and related vicinity properties; and (3) complete ground-water activities in compliance with Environment Protection Agency standards no later than FY 2014.

Residual radioactive material was removed from some of the Title I processing sites to off-site disposal locations. NRC does not require a license for remediated processing sites that do not have disposal cells, but NRC is the regulator if contaminated ground water remains. Ground water compliance action plans, with compliance strategies that range from natural flushing to active remediation, have been or are being developed by DOE for processing sites that have contaminated ground water. These plans require approval by NRC and concurrence by the state and Native American Tribe (when applicable). To date, ground water remedies have been approved and implemented at several former uranium ore-processing sites.

The facilities regulated under Title II of the Act are both conventional uranium mill and in-situ leach facilities that were privately owned and operated under an existing license by the NRC or the Agreement States at the time of the passage of UMTRCA. Both Title I and Title II facilities are subject to NRC regulations in 10 CFR Part 40 and EPA regulations in 40 CFR Part 192. Five Title II facilities have completed reclamation and remediation, and have transitioned under the NRC general license, and are also currently under the management of the DOE Office of Legacy Management.

Office of Surface Mining

Congress passed the Surface Mining Control and Reclamation Act (SMCRA) (30 USC 1300, et seq.) in 1977; the law created the Office of Surface Mining (OSM) in the Department of the Interior. Title IV of SMCRA established the Abandoned Mine Land (AML) program, which provides for the restoration of eligible lands and waters mined and abandoned, or left inadequately restored. The act provides a major source of funding for reclamation of all abandoned mine lands. SMCRA also required a fee be assessed on mined coal and allowed for the use of these funds for abandoned mine reclamation. The funds were set aside for reclamation of coal mines and for the closure of hazardous mine openings (adits and shafts) in other types of mining operations.

Once a state certifies that its coal mine operations were reclaimed, these funds can be used for reclamation at other types of mines where the properties are judged to be abandoned, or had

become inactive prior to August 3, 1977. States can use these funds only for properties where there is no company obligation for cleanup and the property is not listed as a National Priority List site under CERCLA. In 1990, changes to SMCRA extended eligibility to limited sites mined after August 3, 1977. The OSM has established guidelines to be considered when developing plans for abandoned mine land programs and projects. They were issued to provide general guidance to states, Indian Tribes, USDA, and OSM on the administration of reclamation activities carried out under SMCRA. While OSM provides guidelines on reclamation requirements, the states/Indian Tribes use their discretion on the caliber or quality of the work done at each site. Significant use has been made of these funds for reclamation of uranium mines in the state of Wyoming, and on the Navajo Reservation. The Hopi and Crow have also made use of these funds for AML reclamation.

Federal Land Management Agencies

In addition to the Department of Energy, certain agencies of the U.S. Department of the Interior and U.S. Department of Agriculture play important roles in uranium development, and remediation of abandoned mines and mills on lands they administer. Principal among them are Interior's Bureau of Land Management and National Park Service, and Agriculture's National Forest Service. Each of these agencies are responsible for implementing on their lands the various environmental laws which are administered by EPA; these include (among others) the CAA, SDWA, CWA, TSCA, RCRA and CERCLA.

U.S. Bureau of Land Management

The BLM, an agency within the U.S. Department of the Interior, administers over 260 million acres of America's public lands, and about 300 million additional acres of subsurface mineral resources, located primarily in 12 Western States. The BLM's mission is to sustain the health, diversity, and productivity of the public lands for the use and enjoyment of present and future generations. BLM administers public lands within a framework of numerous laws. The most comprehensive of these is the Federal Land Policy and Management Act of 1976 (FLPMA) (43 USC 1744, et seq.), though of importance for uranium extraction is its administration of mineral development under the General Mining Law of 1872, as amended (30 USC 29 and 43 CFR 3860. That law provides the successful mining claimant the right to patent (acquire absolute title to the land) mining claims or sites, including uranium locations, if they meet the statutory requirements. To meet this requirement, the successful claimant must:

a. For mining claims, demonstrate a physical exposure of a valuable (commercial) mineral deposit (the discovery) as defined by meeting the Department's Prudent Man Rule[1] and Marketability Test[2]

b. For mill sites, show proper use or occupancy for uses to support a mining operation and be located on non-mineral land.

c. Have clear title to the mining claim (lode or placer) or mill site.

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[1] Where minerals have been found and the evidence is of such a character that a person of ordinary prudence would be justified in the further expenditure of his labor and means, with a reasonable prospect of success, in developing a valuable mine, the requirements of the statute have been met.

[2] A mineral locator or applicant, to justify his possession must show by reason of accessibility, bona fides in development, proximity to market, existence of present demand, and other factors, the deposit is of such value that it can be mined, removed, and disposed of at a profit.

d. Have assessment work and/or maintenance fees current and performed at least $500 worth of improvements (not labor) for each claim (not required for mill sites).

e. Meet the requirements of the Department's regulations for mineral patenting as shown in the Code of Federal Regulations at 43 CFR 3861, 3862, 3863, and 3864.

f. Pay the required processing fees and purchase price for the land applied for.

The BLM administers this program through its 12 State Offices and the Headquarters office. The program has two essential components, adjudication and mineral examination. A staff of land law examiners in each State Office adjudicates applications for completeness and compliance with the law and regulations. All aspects, except the mineral examination, are handled here. Once the application has successfully passed through the adjudication process, the case is assigned to the BLM field office for a formal mineral examination to verify the discovery of a valuable (commercially viable) mineral deposit on the mining claims and proper use or occupancy for any mill sites. If the Agency's mineral report confirms the discovery of a valuable mineral deposit and/or proper use and occupancy for any associated mill sites, BLM will send the application to the Secretary of the Interior for final review and action. If the applicant is successful on all points, BLM issues a mineral patent for the land applied for. However, since October 1, 1994, Congress has imposed a budget moratorium on BLM acceptance of any new mineral patent applications. Until the moratorium is lifted, the BLM will not accept any new applications.

BLM is attempting to identify, prioritize, and take appropriate actions on those historic mine sites that pose safety risks to the public or present serious threats to the environment. Using the approach outlined in the Interdepartmental Abandoned Mine Lands Watershed Initiative, BLM will work in partnership with EPA, state agencies, tribes, private parties, and other interested groups to accelerate the rate of cleanup of watersheds affected by abandoned hard rock mines. With special emphasis on ensuring that viable responsible parties contribute their share of cleanup costs, federal land managers will add three to five watersheds or major mine cleanup actions to the program each year from 1999 through 2005. Within the selected watersheds, cooperative efforts and available resources will be concentrated first on AML sites and features causing serious environmental impacts, then on mitigation and removal of physical safety hazards.

National Park Service

The NPS operates under authority of the 1916 National Park Service Organic Act (16 USC 1, et seq.) as well as host of other federal statutes. According to U.S. NPS Policy Manual (2000) mineral exploration and development may be allowed in parks only when prospective operators demonstrate that they hold rights to valid mining claims, federal mineral leases, or non-federally-owned minerals. If this right is not clearly demonstrated, the National Park Service will inform the prospective operator that, until proof of a property right is shown, the Service will not further consider the proposed activity. If the Service determines that the proposed mineral development would impair park resources, values, or purposes, or does not meet approval standards under applicable NPS regulations and cannot be sufficiently modified to meet those standards, the Service will seek to extinguish the associated mineral right through acquisition, unless otherwise directed by Congress.

In some parks, all or certain types of mineral development are specifically prohibited by law. Persons may not use or occupy surface lands in a park for purposes of removing minerals outside the park unless provided for in law. General management plans, land protection plans, and other planning documents for parks with mining claims, federal mineral leases, or non-federally-owned mineral interests will address these non-federal property interests as appropriate. Lands with mineral interests will be zoned according to their anticipated management and use, based on their resource values, park management objectives, and park-specific legislative provisions relating to mineral interests. The location of new mining claims pursuant to the General Mining Act of 1872 is prohibited in all park areas.

NPS has its own AML program and is an active participant with broader interdepartmental and national AML program associations. The goals of the program are an inventory of all abandoned mineral land sites in the NPS, the elimination of public safety hazards in such sites, the elimination or reduction of adverse effects from such sites on resources in the parks, education and awareness of the public from the preservation and interpretation of historic and cultural artifacts, and the maintenance of specific abandoned mineral lands for critical wildlife habitat, particularly for threatened and endangered species. Remediation of AML sites on NPS lands is an ongoing effort and its focus has been on above-ground sites and remediation.

National Forest Service

The NFS was established in 1905 and is an agency of the USDA. The Transfer Act of 1905 (16 U.S.C. § 472, 476, 495, 551, 554, 615(b), et seq.) transferred administration of the forest reserves to the Department of Agriculture under the Bureau of Forestry, which became the Forest Service. The forest reserves were subsequently renamed national forests. The NFS manages public lands in national forests and grasslands, which encompass 193 million acres. The mission of the FS is to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. Exploration, development, and production of mineral and energy resources and reclamation of activities are part of the Forest Service ecosystem management responsibility. All NFS lands which (1) were formerly public domain lands subject to location and entry under the U.S. mining laws, (2) have not been appropriated, withdrawn, or segregated from location and entry, and (3) have been or may be shown to be mineral lands, are open to prospecting for locatable, or hardrock, minerals (16 U.S.C. 482). Claims are filed and processed by agreement by the BLM.

The NFS established its combined Environmental Compliance and Protection (ECAP) and Abandoned Mine Lands (AML) programs to reclaim the several thousand abandoned underground and open-pit hard rock, placer, and coal mine sites and related mine and mill waste sites on NFS lands that are causing damage to the environment or risks to public health and safety. The NFS began receiving funds to clean up abandoned mines and other sites contaminated with hazardous materials following the passage of CERCLA. Current funding for AML remediation resulted from an agreement among the NFS, EPA, and the states to focus resources on cleaning up abandoned mines using the watershed ("basin-wide") approach rather than attempting to place each mine site under an individual NPDES water discharge permit. In 1995, USDA and the NFS set an AML program goal: To reclaim by the year 2045 all abandoned mine sites on National Forest System lands that have the potential to release hazardous substances or sediment.

Tribes

Uranium mines were produced on lands of many western Tribes. Principal among them are the Navajo of Arizona and New Mexico, which had the most mines produced of any Tribe. The largest uranium mine in the U.S., the Jackpile Mine, was operated on lands of the Laguna Pueblo in New Mexico. The Spokane Tribe in Washington state had a uranium mill and mines on their land, including the Midnite Mine which is now an EPA Superfund site. Others whose lands hosted uranium mine operations include several Tribes of the Sioux of South Dakota, Hopi in Arizona, Yavapai-Apache in Arizona, Eastern Shoshone and Northern Arapaho in Wyoming, and Ute Tribes in Colorado and Utah. All of these Indian Tribes have had very specific environmental, health, and other concerns related to uranium production facilities on their lands.

As a result of the large number of uranium mines on their Reservation, specialized governmental agencies were created by the Navajo Nation to deal with reclamation and remediation activities, as well as environmental protection on their Tribal lands. Due to that level of effort, the following section provides a brief discussion of their organization.

Navajo Nation

The Navajo Nation occupies approximately 25,000 square miles of land in the Four Corners area of Arizona, New Mexico, Utah, and California. The Navajo AMLRP/Uranium Mill Tailings Reclamation Act Department, within the Navajo Nation Division of Natural Resources, has the authority and responsibility to reclaim abandoned uranium mines. The program operates in coordination with the U.S. Office of Surface Mining, within the jurisdiction of the Navajo Nation pursuant to SMCRA, and the approved Navajo Reclamation Plan and Code.

The Navajo Abandoned Mine Lands Reclamation Program (NAMLRP) identified more than 1,032 abandoned uranium mine sites. As of 2005, 913 sites have been reclaimed. This Navajo agency is also responsible for reclamation and administration of uranium mill sites on Navajo lands under DOE UMTRCA program. To guide cleanup actions NAMLRP developed the Health Physics and Instrumentation Monitoring Plan. The plan specifies that the ALARA principal has been adopted such that every attempt will be made to prevent or minimize project related radiation exposure to the general public.

In 1995, legislation made the NNEPA a separate regulatory branch of the Navajo National government and charged it with protecting human health, welfare, and the environment of the Navajo Nation. In April of that year, the Navajo Nation Council passed a resolution establishing the NNEPA and approved adoption of the Navajo Nation Environmental Policy Act. This Act provides guidance for the NNEPA in addition to recognizing that a clean environment contributes to maintaining harmony and balance on the Navajo Nation. The mission of the NNEPA is as follows: `With respect for Dine' values, protect, preserve, and enhance public health, welfare and the environment for present and future generations by developing, implementing, and enforcing strong environmental laws; to foster public awareness and cooperation through education and motivation." Numerous departments in the NNEPA are responsible for the environmental protection programs across Tribal lands, including radiation protection, disposition of hazardous wastes including those from uranium mines, and protection of water resources.

The U.S. EPA headquarters and Region IX offices have provided assistance as part of the Agency's trust responsibilities to the Navajo Nation concerning uranium mine remediation and other related radiation hazards.

States

State authority to regulate radioactive materials is based on the Constitutional law tenet that any authority or responsibility not specifically assigned to the federal government may be exercised by the states. Many states actively regulate radioactive material through radiation control and other state programs. Control under state law includes naturally occurring and accelerator-produced radioactive materials and other sources of ionizing radiation. As of January 2006, thirty-three states have entered into agreements with the NRC, under which the Commission has delegated regulatory authority over most radioactive materials used in non-federal facilities, as long as the state program is compatible with NRC requirements. Most states also control radioactivity through programs implementing the federal clean air, clean water and other environmental laws authorized by EPA.

A model state radiation control statute, last amended in 1983, has been developed by the Council of State Governments. A comprehensive model state code for all types of radioactivity-containing material and radiation-producing machines has been developed by the CRCPD. For example, Part N of the Suggested State Regulations for Control of Radiation (SSRCR) is specific to TENORM.

As an example from one of the 33 members of the Organization of Agreement States, the Colorado Radiation Control Act designates a state radiation control agency and grants board authority to evaluate and control "...hazards associated with the use of any and all radioactive materials and other sources of ionizing radiation." In the Colorado Act radioactive material means *any* material, solid, liquid or gas, which emits ionizing radiation spontaneously. Ionizing radiation means gamma rays and x-ray and alpha particles, beta particles, high-speed electrons, neutrons, protons, and other high-speed nuclear particles. The Colorado Act requires the Colorado Board of Health to promulgate regulations (for licenses and for exemption from licensing), which are modeled after those proposed by the Conference of Radiation Control Program Directors. Colorado regulates uranium mining, milling, and mill tailings impoundments within its borders.

Whether or not an individual state has assumed regulatory authority from the NRC under an Agreement, each state has explicit statutory authority for regulating sources of ionizing radiation not otherwise regulated by the federal government. Several non-Agreement states (for example, Michigan and New Jersey) have asserted specific authority over TENORM, especially cleanup approaches and disposal. Thirteen have developed regulations specifically for TENORM. The exercise of state authorities is reasonably consistent nationwide, but does vary in some respects. For example, Colorado's statute requires Colorado's rules to be neither more nor less stringent than the CRCPD SSRCR and also authorizes TENORM rules only after their promulgation by the EPA. By contrast, the Illinois Division of Nuclear Safety, now under the Illinois Emergency Management Agency, has no such constraints. Agreement State regulation of AEA materials is to be uniform, consistent, and compatible with that of the NRC.

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

Volume 2:

Investigation of Potential Health, Geographic, And
Environmental Issues of Abandoned Uranium Mines

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Introduction

Uranium is a common element in nature, and has been used for centuries as a coloring agent in decorative glass and ceramics. Today, uranium has uses that range from metal alloys to aircraft counterweights. The most significant modern uses of uranium, however, have been for national defense and electric power generation. The advent of nuclear weapons and nuclear power in the United States resulted in a full-blown exploration and mining boom, starting immediately after World War II and making uranium the most important commodity in the mining industry. The greatest period of uranium production spanned from approximately 1948 to the early 1980s (U.S. DOE/EIA 1992). Through 2005, the industry had generated over 420,000 metric tons (MTs) of uranium to foster U.S. dominance in nuclear weapons technology, and later to feed the growing number of commercial power plants utilizing the enormous energy contained in the uranium nucleus (U.S. DOE/EIA 2003a, 2003b, 2006).

Another legacy of uranium exploration, mining, and ore processing was the creation of unreclaimed land workings wherever the uranium concentration in rock was either found or thought to be economically viable. Thousands of miners and prospectors, as well as large mining companies, searched the United States for veins, lenses, sedimentary deposits, and breccia pipes concentrating the valuable metal, echoing the California gold rush 100 years earlier. In many instances, they left behind unreclaimed and exposed wastes elevated in naturally occurring radioactive materials (uranium and its radioactive decay progeny), exposing people and the environment to its hazards.

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.** Radiation levels presented by NORM are generally referred to as a component of "natural background radiation."

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 (beneficiated) or disturbed in a way that increases the potential for human and/or environmental exposures. This definition differs somewhat from other definitions provided by the National Academy of Sciences (NAS 1999a) and the Conference of Radiation Control Protection Directors (CRCPD 2004) in that it further amplifies the need to include materials which have not been modified by human activities, yet have been disturbed in

such ways that they can be misused by humans, or affect the environment[1]; it does not include a reference to Atomic Energy Act materials, as the definitions are changing (see Volume I and its Appendix VI). Uranium TENORM includes the succession of radioactive decay progeny of the parent uranium.

Under the Atomic Energy Act, the U.S. Nuclear Regulatory Commission (NRC) regulates operations that produce and concentrate uranium and thorium. In accordance with terminology of the Act, the NRC has defined in 10 CFR 40.4 "source materials" as **(1) uranium or thorium, or any combination thereof, in any physical or chemical form, or (2) ores which contain by weight one-twentieth of one percent (0.05%) or more of: (i) uranium, (ii) thorium or (iii) any combination thereof. Source material does not include special nuclear material.** It also defines the "by-product materials" (wastes) of those operations **as tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes.** Byproduct materials are also regulated by the NRC. Underground ore bodies depleted by such solution extraction operations do not constitute "byproduct material" within this definition. Wastes from conventional uranium mining (both surface and underground) are not subject to NRC regulation, but are considered to be TENORM, and thus subject to U.S. Environmental Protection Agency (EPA) and State agency oversight.

Under the Energy Policy Act of 2005, the Atomic Energy Act was amended to place additional discrete (highly radioactive in small, defined volumes) sources of TENORM which had the potential to pose a threat to public health and safety or the common defense and security under NRC jurisdiction. The definition of byproduct materials was further modified to include discrete sources of radium-226, any material made radioactive by use of a particle accelerator for use in a commercial, medical or research activity, or materials which might pose a similar threat to public health and safety or the common defense and security. Specific requirements were provided for determining the appropriate waste disposal methods for these materials which could possibly include uranium mill tailings impoundments. The NRC regulatory definition of byproduct materials to accommodate these amendments was finalized in late 2007 (U.S. NRC 2007a), to reflect the recent amendments. These products and wastes are not the subject of this report.

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[1] The National Academy of Sciences (NAS 1999a) defined TENORM as "…any naturally occurring radioactive materials not subject to regulation under the Atomic Energy Act whose radionuclide concentrations or potential for human exposure have been increased above levels encountered in the natural state by human activities." The International Atomic Energy Agency (2003), although referring to this class of wastes and products as "NORMs", defined them as encompassing "all naturally occurring radioactive materials where human activities have increased the potential for exposure in comparison with the unaltered situation. Concentrations of radionuclides (i.e. TE-NORM) may or may not have been increased." Alternatively, the Conference of Radiation Control Program Directors (CRCPD 2004) has defined them as a naturally occurring radioactive material whose radionuclide concentrations are increased by or as a result of past or present human practices. TENORM does not include background radiation or the natural radioactivity of rocks or soils. TENORM does not include "source material" or "byproduct material" as both are defined in the Atomic Energy Act of 1954, as amended (AEA 42 USC §2011 *et seq.*) and relevant regulations implemented by the NRC. EPA believes the definition should include materials which were disturbed, but not further concentrated by human activities, so that the full scope of hazards from TENORM materials can be considered.

The U.S. Environmental Protection Agency (EPA) has previously issued reports on the uranium mining industry in response to congressional mandates and programmatic needs. In 1983, EPA published its *Report to Congress on the Potential Health and Environmental Hazards of Uranium Mine Wastes* (U.S. EPA 1983a, b, c), as required by the Uranium Mill Tailings Radiation Control Act of 1978. This study provided an important overview of the characteristics and generation of uranium mining TENORM wastes during a period when the uranium mining industry was still near its production peak. A subsequent 1985 *Report to Congress on Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale* (U.S. EPA 1985), carried out pursuant to requirements of the Resource Conservation and Recovery Act of 1976 (RCRA), as amended, provided additional risk information and characterization of uranium mining waste. In 1995, EPA issued the Technical Resource Document *Extraction and Beneficiation of Ores and Minerals: Uranium* as a technical update to provide a means of evaluating wastes that were exempt from or subject to regulation under RCRA (U.S. EPA 1995).

During the period 1989 to 1993, EPA worked on a draft scoping report (SC&A 1993) which compiled information on TENORM in several industries, including uranium mining. A preliminary risk assessment was also developed for certain public and occupational exposure scenarios involving the known radiation levels in those industries. Comments received on the draft from industry, as well as EPA's Science Advisory Board (SAB) (U.S. EPA 1994), resulted in further revisions of the scoping draft, though it was ultimately decided that a final report would not be issued.

Following a review of EPA's guidance for TENORM by the National Academy of Sciences, EPA's response to the NAS study, and discussions with EPA's Science Advisory Board, EPA's Radiation Protection Division decided that a further review of the current hazards associated with uranium mining TENORM was warranted. The SAB (U.S. EPA 2001a) 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 the Agency's technical reports. In addition to most sources of TENORM, EPA is responsible for setting environmental standards under the Uranium Mill Tailings Radiation Control Act, cleaning up hazardous waste sites that include some former uranium mines, and assisting Native Americans, including assisting in environmental reviews of proposed *in situ* leach (ISL) facilities. While this report focuses on the impacts associated with conventional surface and underground uranium mines, as a continuation of Volume I of this technical report (discussed below), and following the recommendations of the SAB, it provides limited background materials, in appendices, on risks associated with uranium milling and ISL operations and wastes generated by those processes, even though they may not be considered TENORM by virtue of their regulation by the NRC and its Agreement States under the Atomic Energy Act and its amendments.

The NRC stated its intent in July 2007 (NRC 2007b) to develop a Generic Environmental Impact Statement (GEIS) on uranium milling which would provide more detailed information on the ISL process and impacts, and may include more recent information on the impacts. The reader is referred to that document when made available to the public in the future for additional background information and associated risk assessment.

This is the second of two reports on uranium mining TENORM. The first report, *Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining, Volume 1: Mining and Reclamation Background* (U.S. EPA 2006a), provides background information on the occurrence of uranium, mining techniques, and reclamation of uranium mines. This report investigates the potential radiogenic cancer risks from abandoned uranium mines and evaluates which may pose the greatest hazards to members of the public and to the environment. The intent of this report is to identify who may be most likely to be exposed to wastes at small abandoned uranium mines, and where the greatest risks may lie. The specific wastes of EPA concern from this report and study are from abandoned conventional open-pit and underground uranium mines, and include overburden, unreclaimed sub-economic ores (protore), waste rock, core hole and drill cuttings, and mine and pit (or pit lake) water. All are described in Volume I of this study. In addition, EPA has compiled and published a uranium location database (U.S. EPA 2006b).

Additional information on uranium milling and extraction waste characteristics, and associated risks for uranium exposures used for this report was obtained from several sources, including industries, EPA contractors, previous EPA reports, federal, state and Tribal agencies, and scientific literature published by various national and international organizations. A first draft of this report underwent an outside peer review following the Agency's peer review process. Using the comments obtained, the report was updated and revised by including new appendices providing references and information on the risks associated with uranium mill operations and ISL operations. The revision was then provided to member agencies of the Interagency Steering Committee on Radiation Standards (ISCORS) Subcommittee on NORM, as well as other selected knowledgeable individuals and organizations, and placed on the EPA Internet site for public comment. Responding to reviewers' comments, we made some changes to the appendices.

While some of the thousands of conventional open surface and underground uranium mines in the United States have been reclaimed, many have not. Any mine may pose such hazards as open shafts and unstable supports (rock and wood), and contain gases, such as carbon dioxide and methane, that displace oxygen and could lead to asphyxiation. In addition to the immediate physical threats that abandoned mines may pose, exposure to radiation from uranium and radium and other contaminants in abandoned mine waste can increase a person's risk of cancer.

People are exposed to naturally occurring radioactive materials in soils, as well as natural occurrences of uranium in rock outcrops. However, the primary focus in this report is on exposures to those naturally occurring radioactive materials that have been enhanced by human activities at abandoned uranium mines. In examining the radiological risks due to mining, the focus is on those concentrations above natural background, as recommended in the EPA *Abandoned Mine Site Characterization and Cleanup Handbook* (U.S. EPA 2000a), with emphasis on uranium and radium. Abandoned conventional uranium mines may also contain other hazardous contaminants, such as metals. For example, the carcinogen arsenic may be a problem at some uranium mines, contributing to increased risks.

This scoping report describes in Chapter 1 several previous studies supporting the risk analysis, while Chapter 2 provides a geographic location analysis of uranium mines in the western United

States. Chapter 3 discusses potential scenarios and exposure pathways for the general public to hazards from uranium mines, describes the methodologies used in the analysis, and assesses cancer risks posed by human exposure to the various hazards from the mines. Chapter 4 examines the use of uranium risks in building materials, and Chapter 5 briefly discusses the potential for ecological impacts from the mines. Uncertainties and conclusions are presented in Chapters 6 and 7.

1.0 MAJOR STUDIES SUPPORTING THIS SCOPING RISK ANALYSIS

The most important period of past U.S. uranium production spanned from approximately 1948 to the early 1980s (U.S. DOE/EIA 1992). Through 2005 the industry had generated over 420,000 metric tons (MTs) of uranium for nuclear weapons and commercial power plants (U.S. DOE/EIA 2003a, 2003b, 2006). Uranium exploration, mining, and ore processing left a legacy of unreclaimed land workings wherever the uranium concentration in rock was either found or thought to be economically viable. This report investigates some potential health, geographic, and environmental issues of abandoned uranium mines.

The major studies supporting this scoping analysis include EPA's 1983 *Report to Congress on the Potential Health and Environmental Hazards of Uranium Mine Wastes* (U.S. EPA 1983a, b, c) and EPA's risk assessments for underground and surface uranium mines for Clean Air Act requirements (U.S. EPA 1989a). Other analyses considered include a report of two uranium mines on the Superfund National Priorities List (U.S. EPA 2001b) and a U.S. Department of Energy report (U.S. DOE/EIA 2000). These studies are discussed in this chapter.

1.1 1983 EPA Report to Congress

The Uranium Mill Tailings Radiation Control Act of 1978 directed EPA to conduct a study on "the location and potential health, safety and environmental hazards of uranium mine wastes," and to provide "recommendations, if any, for a program to eliminate these hazards." When EPA published its 1983 Report to Congress (U.S. EPA 1983a, b, c) (hereafter referred as the 1983 EPA report or study), there were about 340 active uranium mines in the United States. At the end of 2002, there were no active conventional uranium mining operations in the United States, and only two active operations using the *in situ* leaching process (U.S. DOE/EIA 2003a). However, with an increase in the price of uranium since 2004, additional conventional mines have begun production or will be coming on line in the near future, and some suspended mine operations have recommenced. As part of the 1983 study, EPA also made observations at a number of active and inactive uranium mine sites, collected soil and water samples, and took some external gamma and radon flux measurements at sites in Colorado, New Mexico, Texas, and Wyoming.

1.1.1 Sources and Pathways Modeled

In the 1983 report, EPA used the information discussed above to develop models for large and small mines, including an inactive surface mine hypothetically located in Wyoming and an inactive underground mine hypothetically located in New Mexico (U.S. EPA 1983b). From these model mines, which were classified as an average mine or a large mine, EPA estimated the health effects to populations within 50 miles (80 km) of each mine and on a hypothetical most exposed individual living about 1 mile from the center of a mine. The pathways considered were as follows:

- Breathing air containing windblown dust and radon decay products
- Drinking water containing uranium and its decay products

- Eating food contaminated by either air or water
- Living in homes on land covered by mine wastes (U.S. EPA 1983b)

With the exception of the last pathway, the focus of the report was on estimating risks to people who were off site. The home pathway was not explicitly modeled like the other pathways, but used estimates of indoor radon as a function of radium in the soil. While the 1983 report produced many analyses, some issues were not explicitly addressed, including the following:

- Drinking groundwater and surface water near a mine. This pathway was considered and included for the regional population, but was not included for the most exposed individual due to lack of information on radionuclides in potable water.

- Individuals spending time on mine sites.

- Using mine waste material for buildings.

In its 1983 Report to Congress, EPA identified the sources modeled and those considered, but not modeled, due to a lack of information (Table 1.1). For groundwater, the report noted that uranium mines may pose a problem, but the authors did not have enough information to consider it. The report also noted that spending time at the mine sites and using waste materials in the buildings would be a health hazard, but did not quantitatively address the issues.

Table 1-1.   Sources of Contamination at Uranium Mines

In its 1983 Report to Congress, EPA identified the sources modeled (M)
and those considered (C), but not modeled, due to a lack of information.

Sources of Contamination	Underground Mines		Surface Mines	
	Active	Inactive	Active	Inactive
Waste Rock (Overburden) Pile				
Wind-suspended dust	M	M	M	M
Radon-222 emanation	M	M	M	M
Precipitation runoff	C	C	C	C
Sub-Ore Pile				
Wind-suspended dust	M	M	M	M
Radon-222 emanation	M	M	M	M
Precipitation runoff	C	C	C	C
Ore Stockpile				
Wind-suspended dust	M	M	M	M
Radon-222 emanation	M	M	M	M
Precipitation runoff	C	C	C	C
Abandoned Mine Area Surfaces				
Radon-222 emanation	M	M	M	M
Mining Activities				
Dusts	M	NA	M	NA
Combustion products	M	NA	M	NA
Radon-222	M	NA	M	NA
Wastewater				
Surface discharge	M	NA	M	NA
Seepage	C	C	C	C

Note: NA = not applicable.
Source: USEPA 1983b, Table 2.

1.1.2 1983 EPA Study Findings

Using the risk methodology of the time (AIRDOS-EPA, DARTAB, and RADRISK), the study estimated that a large active underground mine posed an increased chance of a fatal lung cancer to an individual of 2×10^{-3}, primarily from breathing radon decay products, and that risks from other types of uranium mines were somewhat lower. Releases to surface water from an average underground mine one mile from an individual's home were estimated to increase his or her lifetime cancer risk by 1×10^{-3}, and that one additional cancer in several hundred years might occur in nearby populations from the normal operational releases from a mine. Although the study did not address the health effects of contaminated shallow aquifers around active or inactive mines, it recommended that they be evaluated.

For inactive mines, the study noted that radionuclide airborne emissions were smaller than for active mines, with the risks coming from radon emanating from unsealed mine vents, portals, and residual waste piles. The estimates of risks from radon emissions from inactive uranium mines were as follows:

- Individuals living for a lifetime 1 mile (1.6 km) from an inactive mine would have an increased chance of lung cancer of about $2-3 \times 10^{-5}$.

- The amount of radon-222 released each year from all inactive uranium mine sites would (cumulatively) cause about 0.1 lung cancers fatalities in the lifetime of the regional population living within 50 miles (80 km) of these sites.

The study found insignificant concentrations of hazardous air emissions at inactive sites and thus concluded that their health impacts would be insignificant as well. Although the study acknowledged the potential for hazards from buildings that use uranium mine wastes as construction material, it did not formally analyze the hazard. However, it did mention that building on contaminated land could increase indoor radon concentration and, thus, increase the risk of lung cancer in the residents (U.S. EPA 1983b). The study referenced an earlier study (out of print) jointly conducted by EPA and the Atomic Energy Commission in 1972, that identified about 500 buildings in several western states that exhibited anomalous gamma radiation readings that appeared to be associated with uranium mine wastes. This is further discussed in Chapter 4 of this volume. Tables 1.2 and 1.3 present the specific lifetime cancer risk estimates due to radioactive airborne emissions for one year of exposure and over a lifetime of exposure.

Table 1-2.   Estimated Lifetime Fatal Cancer Risks from 1 Year of Exposure to Airborne Uranium Mine Emissions

The cancer risk from inactive uranium mine radon emissions are generally low for 1 year of exposure.

Source of Exposure	Risk to Maximum Exposed Individual[a]	Risk to Average Exposed Individual[b]	Collective Risk to Regional Population
Inactive surface mines—total	4.7×10^{-7}	8.9×10^{-10}	1.3×10^{-5}
Particulates and Radon-222	5.5×10^{-8}	6.4×10^{-11}	9.1×10^{-7}
Radon-222 daughters	4.2×10^{-7}	8.3×10^{-10}	1.2×10^{-5}
Inactive underground mines—total	2.8×10^{-7}	1.2×10^{-9}	4.5×10^{-5}
Particulates and Radon-222	1.5×10^{-8}	2.0×10^{-11}	7.4×10^{-7}
Radon-222 daughters	2.7×10^{-7}	1.2×10^{-9}	4.4×10^{-5}

a   An individual living within 1 mile (1.6 km) downwind from the mine.
b   The average individual in the regional population within a 50-mile (80-km) radius of the model mine.
Source: U.S. EPA 1983b, Table 6.11.

Table 1-3.   Estimated Lifetime Fatal Cancer Risks from Lifetime Exposure to Airborne Uranium Mine Emissions

The risk to the average person from uranium mine emissions is low. While the risk to the maximally exposed individual is significantly larger, it is still within the Superfund $10^{-4} - 10^{-6}$ risk range.

Source of Exposure	Maximum Exposed Individual[a]	Average Exposed Individual[b]
Inactive surface mines—total	3.4×10^{-5}	6.3×10^{-8}
Particulates and Radon-222	3.9×10^{-6}	4.5×10^{-9}
Radon-222 daughters	3.0×10^{-5}	5.9×10^{-8}
Inactive underground mines—total	2.0×10^{-5}	8.6×10^{-8}
Particulates and Radon-222	1.1×10^{-6}	1.4×10^{-9}
Radon-222 daughters	1.9×10^{-5}	8.5×10^{-8}

a   An individual living 1 mile (1.6 km) downwind from the mine.
b   The average individual in the regional population within a 50-mile (80-km) radius of the model mine.
Source: U.S. EPA 1983b, Table 6.12.

1.1.3   Applicability of 1983 Risk Estimates

According to Table 6.17 of the 1983 EPA report (U.S. EPA 1983b), radon decay products account for 88 percent or more of the fatal cancer risk due to emissions of radioactive particles from inactive surface and underground mines. Risk estimates given for radon decay product releases from these two types of mines in Tables 6.11 and 6.12 of the report are consistent with the methodology used by EPA prior to 1988. At that time, 4.6×10^{-4} cancers were projected per

working-level month (WLM)[1] of exposure. An analysis of results from the recent BEIR VI report (NAS 1999b, U.S. EPA 2003a) on risks from exposure to radon suggests that the risk factor should be 5.38×10^{-4} per WLM.

Table 1.4 reproduces the working-level estimates of the model inactive surface mines and model inactive underground mines which are provided in Table 6.3 of the 1983 EPA report. The values in Table 1.5 are based on the working-level estimates in Table 1.4. Table 1.5 presents recalculated risks from 1-year, 30-year, and lifetime exposures to radon decay product emissions using the higher, current risk factor. The table does not account for exposures for the portion of time spent outdoors, and for lifetime exposures it assumes an average life span of 75.4 years, which is slightly longer than the 71-year life span used in the 1983 EPA report. The formulas used to derive the results in Table 1.5 are as follows:

$$R_1 = \text{Lifetime risk for 1-year exposure at 1 WL} = 51.56 \text{ WLM/WL-y} \times 5.38 \times 10^{-4} \text{ WLM}^{-1} \times 1 \text{ year};$$

- The risk for 30-year exposure at 1 WL = $R_1 \times 30$ years= 0.83
- The risk for lifetime exposure at 1 WL = $R_1 \times 75.4$ years = 2.09

Thus, the 1-year exposure risk estimate from radon decay products for the maximally exposed individual at an inactive surface mine using the 1.8×10^{-5} WL estimate from the model mine in Table 1.4 would be:

$$R_1 = 1.8 \times 10^{-5} \text{ WL} * 51.56 \text{ WLM/WL-y} \times 5.38 \times 10^{-4} \text{ WLM}^{-1} \times 1 \text{ year} = 4.99 * 10^{-7} \cong 5.0 \times 10^{-7}$$

Risks using this updated estimate and presented in Table 1.5 are about 17 percent higher than in the 1983 report, reflecting the increased risk per working level. One limitation relating to this conclusion is that no adjustment was made in the calculations for differences in the distribution of activity-weighted particle size for indoor and outdoor radon exposures.

Table 1-4.   Annual Exposure from Radon Decay Product Emissions from Model Uranium Mines

Source of Exposure	Average Radon Daughter Concentration (Working Levels)*	
	Maximum Exposed Individual [a]	Average Exposed Individual [b]
Inactive surface mine	1.8×10^{-5}	3.5×10^{-8}
Inactive underground mine	1.1×10^{-5}	5.1×10^{-8}

* A Working Level is defined in footnote 1 of this chapter.
a An individual living 1 mile (1.6 km) downwind from the mine.
b The average individual in the regional population within a 50-mile (80-km) radius of the model mine.
Source: U.S. EPA 1983b, Table 6.3.

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[1] The working level (WL) is defined as any combination of short-lived radon decay products (through polonium 214) per liter of air that will result in the potential emission of 1.3×10^{5} MeV of alpha energy. A person exposed to one WL for 170 hours is said to have acquired an exposure of one working-level month (WLM) (Shapiro 1990). This 170-hour value is based on the typical number of hours underground miners worked in 1 month.

Table 1-5.   Estimated Individual Lifetime Fatal Cancer Risks for Various Exposures to Radon Decay Products

With the modification for the current risk methodology, the lifetime fatal cancer risk from radon decay products is still within or below the Superfund $10^{-4} - 10^{-6}$ risk range. (See the discussion for additional background of the risk estimates.)

Source of Exposure	Exposure Duration	Lifetime Risk of Fatal Cancer	
		Maximum Exposed Individual [a]	Average Exposed Individual [b]
Inactive surface mine	1 year	5.0×10^{-7}	9.7×10^{-10}
	30 years	1.5×10^{-5}	2.9×10^{-8}
	75.4 years (lifetime)	3.8×10^{-5}	7.3×10^{-8}
Inactive underground mine	1 year	3.1×10^{-7}	1.4×10^{-9}
	30 years	9.2×10^{-5}	4.3×10^{-8}
	75.4 years (lifetime)	2.3×10^{-5}	1.1×10^{-7}

a   An individual living 1 mile (1.6 km) downwind from the mine.
b   The average individual in the regional population within a 50-mile (80-km) radius of the model mine.
Source: U.S. EPA 1983b, Table 6.17.

1.2   1989 EPA Study in Support of NESHAPs

In 1989, EPA conducted risk assessments for active underground uranium mines and surface uranium mines (U.S. EPA 1989a), in support of the National Emission Standards for Hazardous Air Pollutants (NESHAPs) for Radionuclides (U.S. EPA 1989b, c). While some of the information in this investigation was based upon U.S. EPA 1983 (a, b, c), the study also included some new field work and analysis. The study found that of all the radionuclides emitted, radon decay products posed the greatest cancer risk. The maximum exposures from underground mines would create lifetime individual fatal cancer risks of greater than 1×10^{-4}, with a maximum of 4×10^{-3}. The maximum individual risk of fatal cancer from radon decay products at surface uranium mines was estimated to be 5×10^{-5}; this risk estimate, too, would be slightly higher, given the current methodology. The 1989 study found that only a limited number of people lived within several hundred feet of the mines and would have been exposed to the maximum levels; most of the nearest residents lived several miles from the mines.

1.3   Uranium Mines on the National Priorities List

Although several uranium mill tailings sites are on the Superfund National Priorities List (NPL), only two uranium mines are on the list: Midnite Mine, near Wellpinit, Washington, and the Fremont National Forest—White King/Lucky Lass Mines, Oregon. Both sites have progressed far enough in the Superfund process to have had a cleanup remedy selected in a Record of Decision (U.S. EPA 2001b, U.S. EPA 2006c). Figures 1.1 and 1.2 are aerial images of Midnite Mine and the White King/Lucky Lass Mine sites, respectively.

Figure 1-1.   Aerial Image of Midnite Mine, Washington State

Midnite Mine is on the NPL. The site has uranium and other heavy metal contamination in the disturbed area and two pit lakes.

Source: Photo courtesy of EPA Region 10 Superfund Program.

No one is currently living at the White King/Lucky Lass site, nor is a future resident anticipated, given that the site is on U.S. Forest Service property and is not near population centers. However, the risk assessment did assume a future resident as a scenario. In addition, the receptors evaluated included a site worker (e.g., timber or U.S. Forest Service employees) and a recreational user. The following areas were used as exposure points (U.S. EPA 2001b):

- The protore stockpile at the White King Mine
- The overburden stockpile at the White King and Lucky Lass mines
- Off-pile areas at the White King and Lucky Lass mines

The primary chemicals of concern at the White King/Lucky Lass site were arsenic in soil and shallow groundwater, uranium-234/238 in stockpile groundwaters, radium-226/228 in soil and shallow bedrock wells, and radon in water. Of note, and in spite of several high radon flux rates, inhalation of radon in ambient air was not an issue, since radon concentrations from the stockpiles were equivalent to background concentrations.

Figure 1-2.   Aerial Image of White King and Lucky Lass Mines, Oregon

*The Lucky King Mine pit lake is approximately 5,000 feet (1,500 meters)
northwest (left) of the White King Mine pit lake.*

Table 1.6 summarizes the risks at the mine sites for the human receptors. With the approach used in the Record of Decision, the exposure assessment indicated an extremely high risk to future potential residents and child recreational users. The high risks were primarily due to ingestion of arsenic in soils and shallow groundwater and external radiation from radium. In the ecological assessment, no adverse effects were seen from the radionuclides. However, some potential adverse ecological effects were identified due to arsenic, selenium, antimony, lead, and mercury in surface and subsurface soils at the White King Mine. At Lucky Lass, only slightly elevated risks (the noncarcinogen chemical hazard index ranging from 1 to 3) were predicted for the vagrant shrew and terrestrial plants exposed to arsenic and silver in surface soil. In contrast, Midnite Mine has a greater potential for future use, but the cancer risks were predicted to equal 8 $\times$ 10^{-1} for a resident of the affected area and 2 $\times$ 10^{-3} for recreational visitors.

Table 1-6. **Potential Cancer Risks from the White King/Lucky Lass and Midnite Mine Sites**

The combination of arsenic and radium produces very high cancer risks to potential on-site residents.

Receptor	Total Cancer Risk	Pathway	Notes
White King Mine current adult worker	6×10^{-5}	Ingestion of arsenic in soil and exposure to external radiation from radium-226/228 in the top 6 inches of soil.	Current exposure estimates for soil are based on 0–6 inches; future exposure estimates for soil are based on 0 - 6 feet.
Future recreational user (child) at the White King Mine	4×10^{-4}	Arsenic in soil, exposure to external radiation from radium-226/228 in soil and ingestion of arsenic in Augur Creek and White King groundwater. Ingestion of arsenic in soil and exposure to external radiation from radium-226/228 in the top 6 feet of soil, ingestion of arsenic in shallow bedrock groundwater, inhalation of radon in shallow bedrock groundwater, and exposure to arsenic in White King pond surface water and sediment.	Deep bedrock water contains high levels of naturally occurring arsenic, radon, and minerals that would preclude its use as drinking water.
Potential future resident (adult) at the White King Mine	3×10^{-1}		
Potential future resident (child) at the White King Mine	2×10^{-1} Hazard Index values for noncarcinogenic effects to current and potential future child recreational users were 4 and 11, respectively, and higher for potential future residents from ingestion of arsenic and manganese in shallow bedrock groundwater and ingestion of arsenic in soil.		
Potential future resident at the Lucky Lass Mine	1×10^{-3}		
Potential future resident at the Midnite Mine Area	1		

Note: A Hazard Index value below 1 indicates no adverse health effects are expected as a result of exposure.
Source: U.S. EPA 2001b.

1.4   DOE Report on Costs of U.S. Uranium Mine Environmental Restoration

A report commissioned by the U.S. Department of Energy (DOE) found that a number of uranium mines are undergoing or have completed remediation (U.S. DOE/EIA 2000). According to the report, 21 mines, primarily in Wyoming and Texas, were selected for analysis for one or more of the following reasons: (1) substantial output of uranium concentrates, (2) major impact on the environment, and (3) significant costs required for remediation. While the report does not specify whether these sites are undergoing risk assessments, it does specify whether a particular site has an exposure pathway of surface water, groundwater, or windblown particulates. The information lists groundwater as an exposure pathway for many of the mines, while the surface water and windblown particulate pathways are not as prevalent.

2.0 GEOGRAPHIC ANALYSIS ON THE LOCATION OF URANIUM MINES

With the exception of some phosphate mine areas in central and northern Florida, people are most likely to be exposed to uranium mining-related TENORM in the western United States. This chapter provides a geographic analysis of the spatial locations of western mines in proximity to human populations, cultural and political features and boundaries, and environmental features. The use of geographical information system (GIS) software provides a systematic means to understand the potential impacts and scenarios by which humans and the environment may be impacted by uranium mines.

Figure 2.1 was generated from uranium mining-related records from the U.S. Bureau of Mines—now U.S. Geological Survey (USGS)—Mineral Availability System/Mineral Industry Location System (MAS/MILS) database from the EPA BASINS data (U.S. EPA 2001c). While about half of the 8,234 locations are documented as producing ore, the remaining records may identify mines or simply locations with uranium. Of the 8,234 records, 4,141 are categorized as "producer" or "past producer," and these terms are being used as proxies for known mines. Another 63 records are classified as mills or processing plants, and once these are removed, the 4,078 records that are left are assumed to be former mines. Of the 4,078 mines, about 3,000 are in Colorado, Utah, Arizona, and New Mexico. Similar information comes from the Department of Energy's (DOE) Energy Information Administration database (Smith 2002), which has 3,502 records for Colorado, Utah, Arizona and New Mexico. Within this set, 2,952 mines had at least some ore production (Table 2.1), similar in number to the MAS/MILS data.

Table 2-1. Mine Sizes for Four-Corners States

Of ~3,500 uranium mines in Colorado, Utah, Arizona, and New Mexico, 2,952 mines had at least some ore production.

Ore Production (Tons)	Number of Mines
<100	1,192
100–1,000	615
1,000–100,000	952
>1,000,000	5
Data withheld as confidential business information.	188
Total	**2,952**

Source: Smith 2002.

The definition of a mine leads to problems with determining how many mines really exist. Even a single data set may have different interpretations for what could be considered a mine. Records may indicate multiple mine portals for an underground mine, for example. EPA has compiled a database of uranium locations from different sources totaling about 15,000 records, from which an attempt has been made to remove redundant records (U.S. EPA 2006b). The EPA database thus lists several thousand more mines than any other data set. Table 2.2 compares the number of records by state for the USGS MAS/MILS database (U.S. EPA 2001c) and unpublished USGS data sets by Finch (1998). The BASINS MAS/MILS database typically lists more mines than the Finch data set, although Finch has noted more mines in Texas and South

Dakota. The EPA ULD Compilation (U.S. EPA 2006b), as sorted for this analysis,[1] contains nearly 11,000 records, and typically has more uranium locations per state than the other data sets.

Figure 2-1.   Mines and Other Locations with Uranium in the Western U.S.

Hundreds of active and abandoned uranium mines are scattered over wide areas of the western United States.
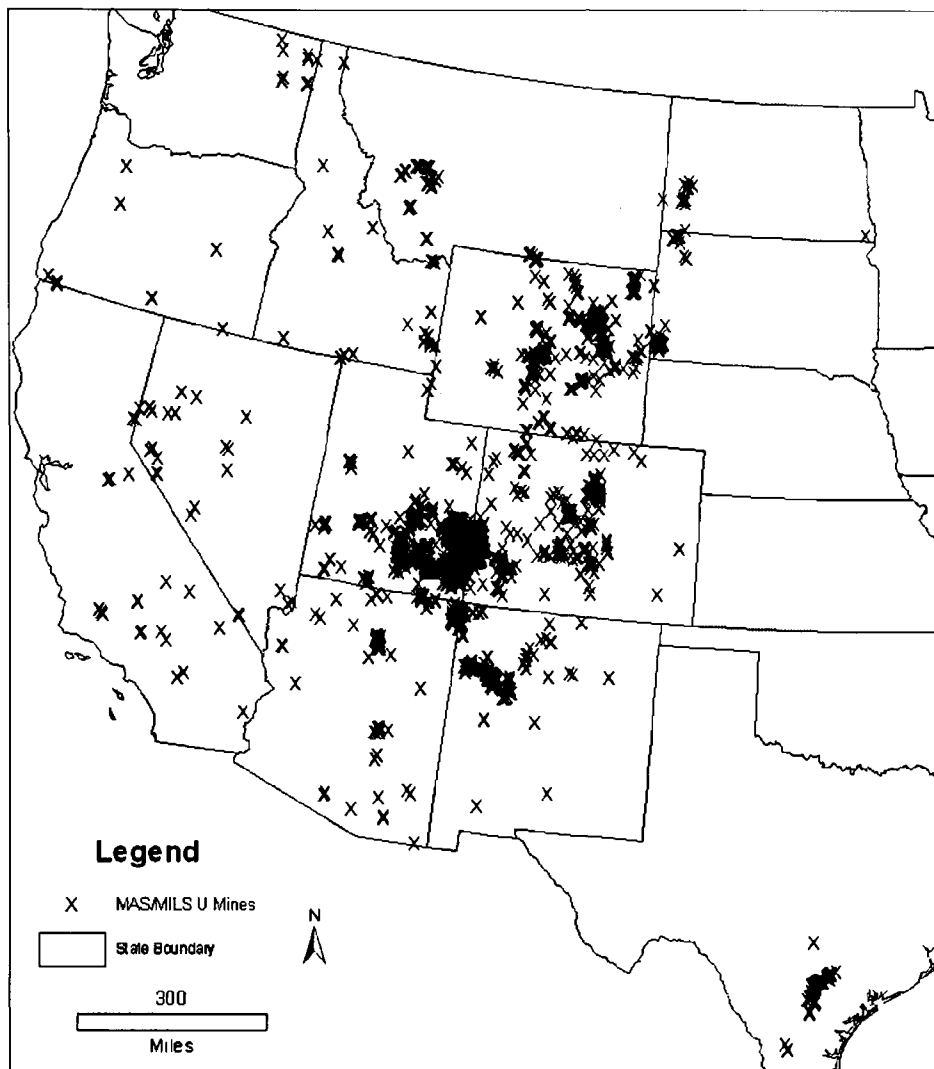
Source: MAS/MILS Database.

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[1] For this comparison, the EPA ULD Compilation was sorted to delete the Mineral Resource Data System (MRDS) data, because many of the records were identified as simply drill holes, or mineral locations and also included many eastern locations not relevant to this study. In addition, location names that were variations on unknown or unnamed in the MINE NAME field in the ULD were removed so that the remaining records were more likely to be actual mining sites. For example, records with MINE NAME fields with entries such as "UNKNOWN," "UNKNOWN NAME," "UNNAMED PROSPECT." and "UNNAMED URANIUM OCCURRENCE" were deleted.

Table 2-2.   Comparison of Data Compiled from Uranium Mine Records

Different data sets have different estimates of the number of uranium mines.

State	BASINS MAS/MILS		Finch	EPA ULD Compilation
	All Records	Producer or Past Producer		
Arizona	466	146	403	1,104
California	243	23	59	268
Colorado	2,286	1,631	1,262	2,268
Idaho	234	34	6	216
Missouri	2	0	0	2
Montana	195	47	31	482
Nevada	363	24	20	396
New Mexico	756	337	330	2,247
North Dakota	23	16	13	109
Oklahoma	2	0	8	0
Oregon	100	15	6	56
South Dakota	197	130	203	307
Texas	69	69	90	136
Utah	1,542	911	1,120	2,047
Washington	68	13	20	98
Wyoming	1,616	682	625	1,172
Totals	**8,162**	**4,078**	**4,196**	**10,908**

Sources: U.S. EPA 2006b, U.S. EPA 2001c, and Finch 1998.

2.1   Errors in Mine Locations

The mine record data used for most of the geospatial analyses, have two distinct error types. In addition to the definition of "mine" that was discussed above, there are errors of omission and commission (i.e., erroneous locations in the database, as well as actual mines not represented). However, accuracy of the data was checked in the EPA ULD compilation (U.S. EPA 2006b), and the mines were typically found to be within several hundred meters of mines identified on U.S. Geological Survey maps. The primary endpoint of the analyses described in this document is in terms of the radiation dose to an individual, not the collective dose to a population group. For this reason, errors in the total number of mines will not have a significant effect on the overall conclusions. There are also location precision errors (i.e., a listed mine not in its actual location as shown on USGS maps, for example). The latter are not likely to affect the analyses in this document because of the focus on risks to individuals, not populations.

2.2   Number of People Potentially Exposed to Uranium Mine Wastes

The 1983 EPA study found that, for releases to air and surface waters, the cancer risks were less than 10^{-4} and 10^{-6} for people living 1 mile or farther from active and inactive mines, respectively. Based on this information, we have assumed that the populations primarily at risk live within 1 mile (1.6 km) of uranium mines and, thus, have estimated the number of people within 1 mile of a uranium mine. We have also estimated the number of people who live nearby (within 5 miles

[8 km]) to help identify a likely population that may engage in recreational or other visitation activities in areas with unreclaimed uranium mines.

To estimate the number of people who live in proximity to uranium locations, we queried the 4,078 records in the MAS/MILS mine database in ArcView 8.2, ArcView 9.1, and Spatial Analyst (collectively, ArcView), using population data from the 2000 census (ESRI 2001). About 800,000 people are estimated to live within 5 miles of a uranium mine, and about 55,000 (or about 10 to 15 people per mine on average) are estimated to live within 1 mile of such a mine. About 10,000,000 people are estimated to be within 50 miles (80 km) of a recorded mine, with 502 of 4,078 mines located within 50 miles (80 km) of cities whose population is greater than 30,000. A search indicates that 33 of the recorded mines are within 1 mile (1.6 km) of a U.S. Bureau of Census "place" in the ArcView database, most of which are in Colorado; 141 of the mines are within 5 miles of a place (Table 2.3). In comparison, an analysis of the 10,908 "mine" locations from the ULD found that the population within 1 mile (1.6 km) and 5 miles (8.0 km) of a uranium location was 227,692 and 3,993,642, respectively.

The low number of people living within 1 mile (1.6 km) of a mine can be attributed to the fact that 7,076 of the MAS/MILS 8,234 records (86 percent) are located on federal land, while about 90% of the mines with known production are on federal land (Table 2.4). In the ULD data set, 8,124 of the 10,908 locations (74.5%) of the locations were on federal land (Figure 2.2 is a map of the ULD locations and federal lands). A query of the 7,076 mine records using ArcView revealed that 6,127 mines could be attributed to a specific federal land management agency, with most on U.S. Department of the Interior lands or Forest Service lands (Table 2.4). With the majority of the mines on federal land, people who use these sites for recreation would most likely be subjected to the greatest potential for exposure to uranium mine wastes. An exception to this would be the uranium mines on Tribal lands, where the Tribal members would receive the greatest exposure potential. Five percent (221) of the 4,078 mine records in the MAS/MILS database are on Bureau of Indian Affairs land, while eight percent (898) of the 10,908 records of the EPA ULD used in this analysis are on Bureau of Indian Affairs land.

Of the 69 mines in the MAS/MILS data identified in Texas, none are on federal lands. Over one half of the past-producer mines in Wyoming (456 of 682) are on federal lands. Of the 1,631 mines in the past-producer Colorado data set, 1,572 are on federal lands.

2.3   Mines by Watershed

One method used to view the potential for impact by mining on a region and to identify the most likely areas to be affected is on a watershed basis using geographic information system technology (Ferderer 1996). In Figure 2.3, uranium mines have been grouped in watersheds identified by 8-digit hydrologic unit codes (HUCs). Several watersheds have more than 100 uranium mines while a number of others have more than 50 mines. As might be expected from the discussion above, the highest watershed mine density is in Colorado, Utah, and Wyoming. In the watersheds with only a few mines, the mines typically produced uranium as a by-product of other mining, such as copper. One example is the Lefthand Creek mining area along the Front Range in Colorado where gold and silver were the primary metals mined, but also mined were tungsten, copper, fluorspar and uranium (U.S. EPA 2003b). Watersheds are also a unit considered in mine remediation (U.S. EPA 2003b, Buxton et al. 1997).

Table 2-3. Estimated Number of People within 1 Mile (1.6 km) and 5 Miles (8 km) of a Recorded Mine

The 4,078 mine records in the BASINS MAS/MILS database and 10,908 records from the EPA Uranium Location Database Compilation (U.S. EPA 2006b) were queried for the number of people near the uranium locations. Colorado accounts for most of the population living near current and past uranium mines.

State	People within 1 Mile *From 4,078 Records Using Producer or Past Producer and 2000 Census Data*	People within 1 Mile *From 10,908 Records of EPA ULD and 2000 Census Data*	People within 5 Miles *From 4,078 Records Using Producer or Past Producer and 2000 Census Data*	People within 5 Miles *From 10,908 Records of EPA ULD and 2000 Census Data*
Arizona	1,045	21,727	12,160	438,581
California	1,068	34,867	59,437	758,545
Colorado	33,191	67,319	518,357	1,188,827
Idaho	494	5,399	5,803	89,486
Montana	891	5,954	8,233	89,573
Nevada	188	17,369	11,332	577,189
New Mexico	6,013	46,736	84,869	512,102
North Dakota	1,114	1,262	2,159	3,518
Oregon	370	1,134	6,162	30,894
South Dakota	2,889	2,956	5,954	8,538
Texas	591	871	11,700	32,640
Utah	1,387	7,169	22,376	106,015
Washington	162	5,144	3,472	79,200
Wyoming	5,196	9,785	61,701	78,534
Totals	**54,599**	**227,692**	**813,715**	**3,993,642**

Figure 2.4 illustrates one region of high-density uranium locations in drainages in southwest Colorado and eastern Utah. Figure 2.4 contains surface and underground mines, in addition to mines whose types are listed as "unknown" in the MAS/MILS database. This region typically has horizontal rock layers that have been incised by streams exposing the uranium-bearing layers, such as the Chinle Formation. In this figure, flat-lying areas appear generally featureless, whereas areas incised by streams show relief and appear to be v-shaped. Many of the mine locations are adjacent to streambeds where the mining has taken advantage of exposed uranium layers. The slopes along the canyon walls could enhance movement of radioactive materials to streambeds via mass-movement processes. Since radium and uranium may largely precipitate out of solution or adhere to particles and come to rest in sediments, benthic organisms may be the most potentially affected. However, large-magnitude events (e.g., flooding) could resuspend the material and move it around the streambeds, with higher concentrations likely developing in slack-water deposits where the water flow slows.

Figure 2-2. Uranium Locations from EPA Database and Federal Lands

*About three-fourths of the uranium locations in the EPA Uranium Location Database
are on Federal Lands. Thus, the most likely exposure or risk scenario for many of
the uranium mine locations is the recreational scenario, such as hiking,
camping, use of all-terrain vehicles or other short-term activity.*

**Federal Land Management Agencies
With Significant Uranium Locations**

- Bureau of Indian Affairs
- National Park Service
- Forest Service
- Bureau of Land Management
- ▲ EPA ULD Locations (10,908 Records)

Miles
250
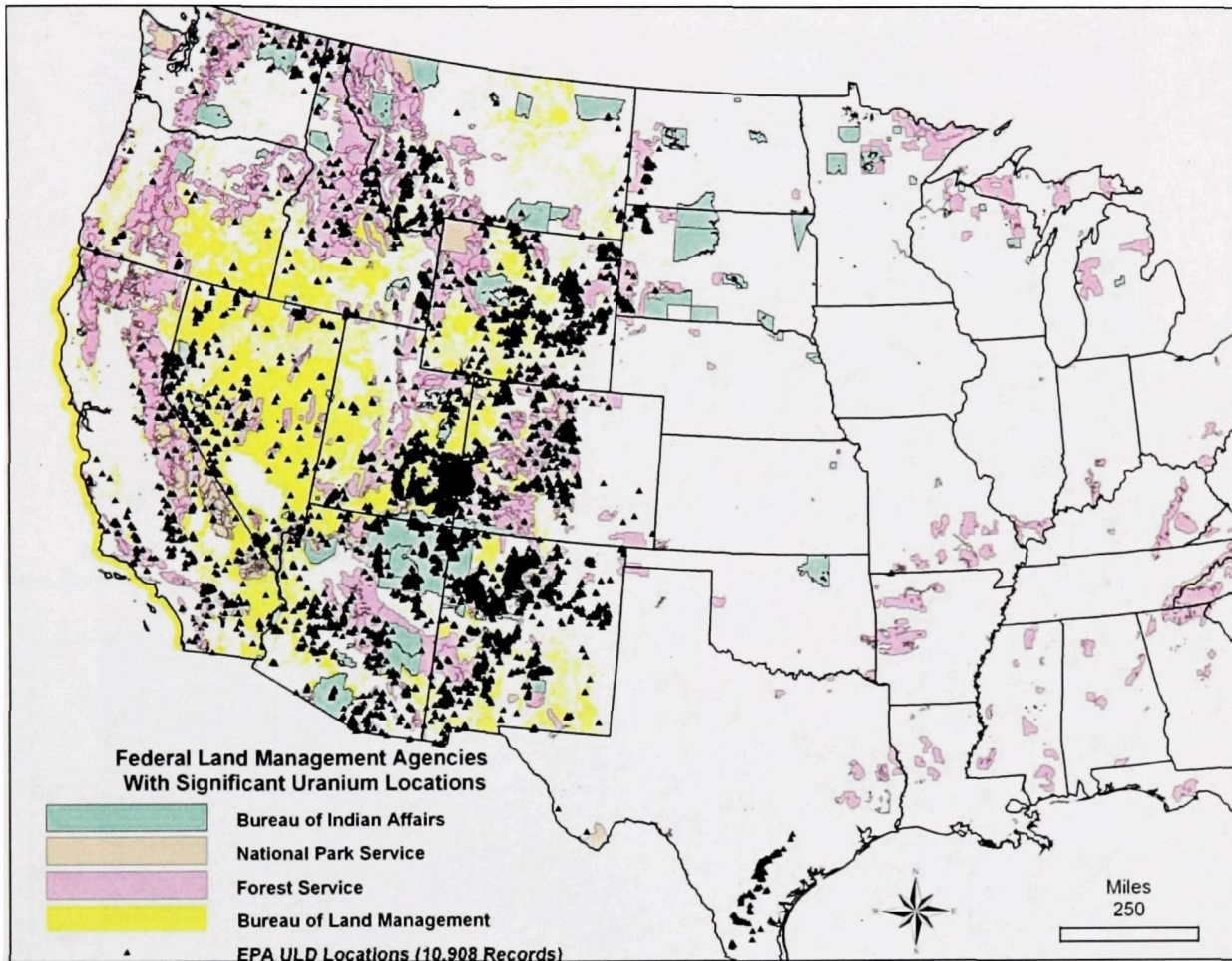
Table 2-4. Number of Mines on Federal Lands in Selected States

Most of the uranium mines on federal lands can be attributed to a specific federal land management agency; the U.S. Department of the Interior and U.S. Forest Service are the two primary land management agencies.

Federal Land Management Agency	From 8,234 Records in BASINS MAS/MILS Database	From 4,078 Records Using Producer or Past Producer and 2000 Census Data
Department of Interior		
Bureau of Land Management	4,241	2,405
Fish and Wildlife Service	7	0
Bureau of Indian Affairs	446[a]	223
National Park Service	121[b]	43
Bureau of Reclamation	3	1
Department of Defense	12	6
Forest Service (USDA)	1,297	515
Unknown	949	500
Total	**7,076**	**3,693**

a   Primarily on Navajo lands.in Arizona, New Mexico, and Utah, in that order
b   Primarily in Utah and California, with California primarily having unnamed prospects.

Figure 2-3. Western Uranium Mine Density by 8 Digit Hydrologic Unit Code

The greatest number of mines (745) in the MAS/MILS data is found in the Upper Dolores Watershed, located primarily in southwest Colorado with a small area in Utah. Other watersheds with more than 300 uranium mines are the Lower Dolores (Colorado and Utah) and San Miguel (Colorado) Watersheds.
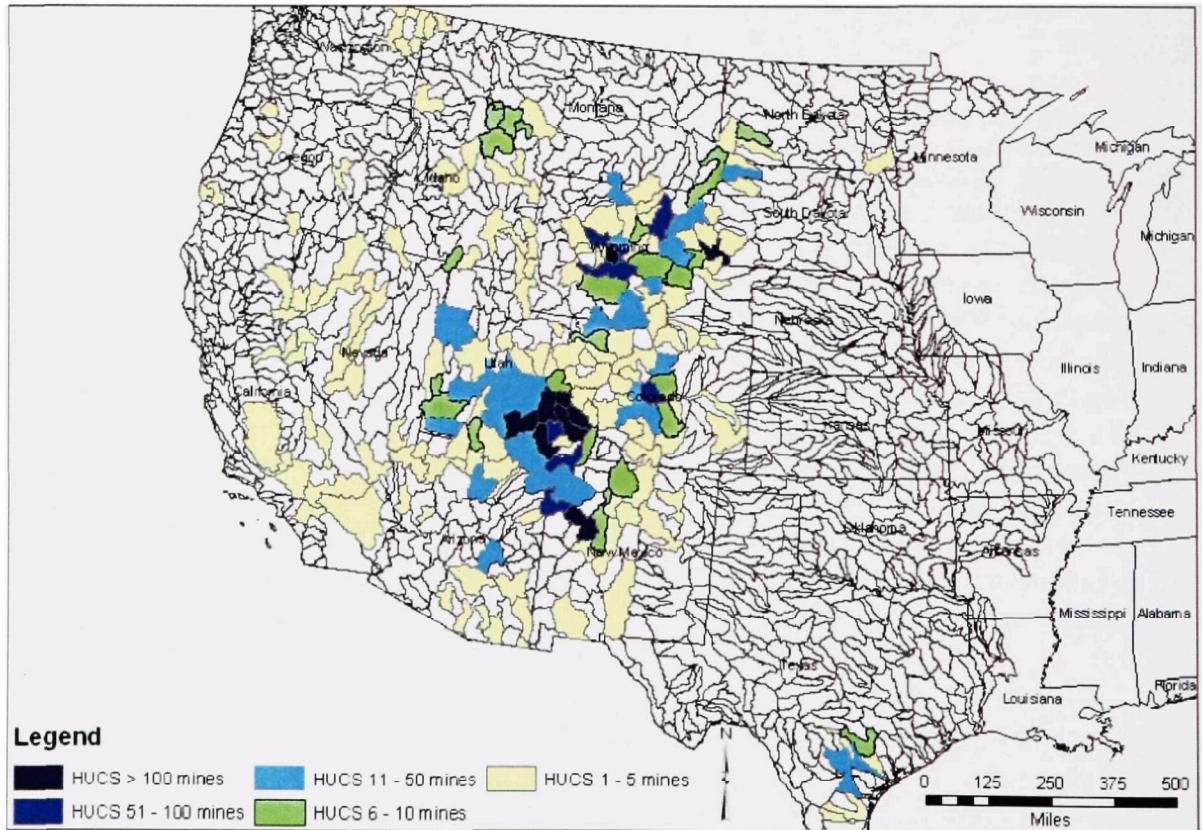
Figure 2-4.   Uranium Locations in Southwest Colorado and Southeast Utah

This region typically has horizontal rock layers that have been incised by streams exposing the uranium bearing layers, such as the Chinle Formation. Flat-lying areas appear generally featureless, whereas areas incised by streams show relief and appear to be v-shaped. Many of the mine locations are adjacent to streambeds where the mining has taken advantage of exposed uranium layers. Mines from the MAS/MILS data are superimposed on digital elevation data.
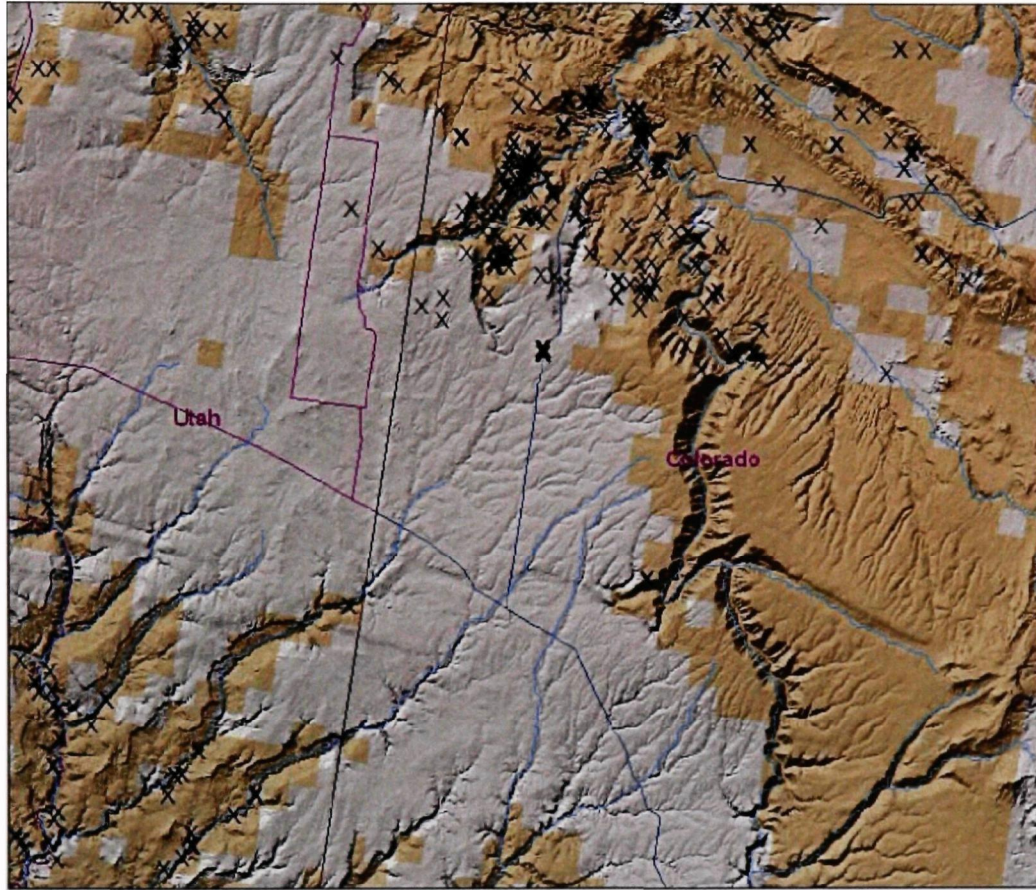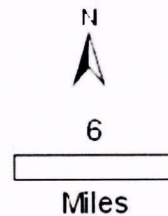
3.0 CANCER RISKS FROM ON-SITE EXPOSURE

This chapter examines the potential scenarios, exposure pathways, and risks of cancer to humans that may be posed by exposure to TENORM from abandoned uranium mine wastes.

3.1 Potential Scenarios and Exposure Pathways for the General Public

Given our knowledge of uranium mine TENORM wastes,[1] there are several possible exposure scenarios for humans to the various hazards posed by these materials: on-site recreation, homes with contaminated building materials, on-site residents, and near-by residents.

3.1.1 On-Site Recreation

Since most uranium locations are on federal lands, the primary exposure scenarios to TENORM wastes at uranium mines would involve recreational use of the site, in which the abandoned mine is visited occasionally by hikers, campers, or driven through by all-terrain vehicles (ATVs). Recreational use by children may occur if a site is located near houses, as, for example, on Tribal lands in Arizona and New Mexico. A typical recreational scenario might take place at the White King and Lucky Lass mines in Oregon, which are on national Forest Service land and can be accessed only by hikers. A less common but more troubling recreational case involved the pit lake at the Yazzie-312 surface mine in Cameron, Arizona, which was approximately 300 feet (~100 meters) across and referred to by local citizens as the "swimming hole" (see Figure 3.1). The site, just off a highway, attracted swimmers because the area lacks natural lakes or streams, other than during periods of the year when the rainfall is heavy. The pit has since been filled and the area reclaimed. Users would likely visit unreclaimed uranium mines for short periods of time, such as two weeks, which is the common maximum time for which the National Park Service issues backcountry permits. Occupational workers, such as government employees or contractors performing site investigations, could also spend similar periods of time at these locations. The primary exposure pathways would be external exposure and drinking contaminated water from an adjacent spring or stream. Pathways of secondary importance include inhalation of dust, exposure to radon, ingestion of dust on dried or prepared foods, and inadvertent ingestion of soil.

3.1.2 Building Materials

A second scenario that has been known to occur, but whose frequency is unknown, is the use of uranium mine waste materials for building construction. Although most of the uranium locations are in areas where recreation is the most likely scenario, some uranium locations are near roads, including unimproved dirt roads, or near rural communities where waste material could be accessed. These materials could be transported from a nearby site and used in the construction of houses, when other building materials are difficult or too expensive for a homeowner to obtain. A discussion of risks from uranium mine wastes in building materials is presented in Chapter 4 of this report.

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[1] Characteristics and origins of wastes mentioned in this study are more fully described in Chapter 3 of Volume I of this report (U.S. EPA 2006a).

3.1.3 On-Site Residents

A third scenario involves on-site residents. Given such factors as the nature of uranium mine waste materials, the isolation of many of the sites, the lack of potable water in many cases, and the lack of infrastructure, this scenario may have a low probability, except for some Tribal populations. The risks for such a scenario would be at the highest end of the risk spectrum and would provide an upper bound for risks. The White King Mine analysis of risks found that a future resident at the White King Superfund site would have an extremely high risk of developing cancer (see Table 1.6). Subpart B of Title 40 of the Code of Federal Regulations, Part 192 (40 CFR 192), which establishes cleanup standards for uranium processing sites, uses a radium surface soil standard of 5 pCi/g (185 Bq/kg) above background, or below, as the cleanup level, with the emphasis on preventing elevated radon levels. This radium cleanup level has been used as a relevant and appropriate requirement to establish cleanup criteria at some Superfund sites. The radon flux standards in 40 CFR 192 assume sand-like uranium mill tailings and limit the radon flux rate to 20 pCi m^{-2}s^{-1}. Uranium mine overburden, or protore, has elevated radon flux rates in a similar range as uranium mill tailings, although the average flux rates may be lower as described by SC&A (1989) and U.S. EPA (2006a, Chapter 3).

Figure 3.1. Uranium Mine Pit Lake

Pit lake of Yazzi-312 surface mine in Cameron, Arizona, referred to by local citizens as the "swimming hole." Suspended sediment transformed the pit water to a milky white color. The pit lake has been reclaimed.

Photograph by Loren Setlow (U.S. EPA)

The last scenario involves people living next to a uranium mine, which has been found to occur in the Navajo Nation. People may live within a short distance of overburden piles and be exposed to uranium from windblown particulates (inhalation of dusts), contaminated water, and external radiation.

The 1983 EPA Report to Congress studied this scenario as part of an investigation of risks to the hypothetically maximally exposed individual located 1 mile (1.6 km) from the center of average and large active and inactive mine sites (EPA 1983a, b, c). The 1983 EPA Report to Congress examined ten pathways. The study looked at risks from pathways including inhalation of radon decay products, external exposure, eating food grown in the area, fish consumption, and drinking milk and eating meat from cattle that had grazed in the area and consumed contaminated water. The study concluded that most of the pathways did not pose great risks.

The study found that radon posed the greatest risk in all scenarios, with large active underground mines emanating the highest concentrations. The maximally exposed individual's risks from radioactive airborne emissions from inactive surface and underground uranium mines were modeled and estimated to be 3.4×10^{-5} and 2.0×10^{-5}, respectively. These risk estimates assumed exposure for 71 years to inactive mine effluents. Similar results were calculated in the 1989 NESHAPs (National Emission Standards for Hazardous Air Pollutants) study (U.S. EPA 1989c). As discussed in Chapter 1, the estimated risk per working level has increased, so these risks would be slightly higher than those identified in the 1983 report and in the 1989 study (U.S. EPA 1989a). The updated risk estimates for inhalation of radon decay products from the 1983 study are listed in Table 1.5. However, since this scenario was considered in the 1983 Report to Congress and in the 1989 NESHAPs study, it is not considered further in the present analysis.

3.2   Methodology Used in This Analysis

This report focuses on risks that uranium mine TENORM wastes could pose for those people who visit inactive uranium mine sites. This analysis complements the 1983 EPA study, which looked primarily at off-site exposures from uranium mines, although it acknowledged the potential on-site health hazards. A key purpose of this approach is to help prioritize the types of uranium mine site wastes and exposures that pose the greatest risk. While some of the analysis examines residential exposure on a site, the focus is more on non-residential uses for the reasons discussed in this section.

Given the limited available data, multiple site characteristics, and the multimedia exposure pathways, multiple approaches were taken to evaluate the risks at these sites. These include reviewing existing data discussed earlier, using geographically-based queries of uranium mine and population data, the Superfund Soil Screening Guidance (SSG) approach for chemicals and radionuclides whenever applicable (U.S. EPA 1996a and 2000b), risk calculations produced for the radionuclides in drinking water regulation (U.S. EPA 2000c), and the use of RESRAD BUILD 3.21 (Yu et al. 1994) for examining building materials. This approach uses applicable peer-reviewed methodologies. The equations in the *Soil Screening Guidance: User's Guide* (U.S. EPA 1996a), *Soil Screening Guidance for Radionuclides* (U.S. EPA 2000b), and *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites* (U.S. EPA

2002) were used, because they are appropriate for looking at generic sites when only limited site-specific data are available. Since the intent of this analysis is meant to be scoping in nature and the information on the sites is limited, the SSG approach is appropriate for identifying the situations that may be of concern. Since this approach is for screening purposes where the intent is to ensure that potential problems are identified, the SSG methodology tends to lead to conservative risk estimates, or risks that are more likely to be overestimated. The risk estimates become more accurate with more site-specific data. Please note that all quantified risks included in this report refer to lifetime cancer risk.

An approach used at Superfund and RCRA (Resource Conservation and Recovery Act) sites is to identify preliminary remediation goals (PRGs) that are intended as initial guidelines, and not necessarily as final cleanup levels. PRGs are risk-based concentrations (assuming a target lifetime risk of 1 x 10^{-6}), derived from standardized equations similar to those found in the *Soil Screening Guidance for Radionuclides* (EPA 2000b). An Internet-based PRG calculator and tables of default values for radionuclides can be found at http://epa-prgs.ornl.gov/radionuclides. A major difference between the SSG methodology and the PRG approach is that the SSG methodology allows examination of an individual pathway, while the PRG uses an all-pathway approach. Since part of the intent of this analysis was to investigate individual pathways, the SSG approach was used. In addition, the PRG approach does not have a recreational scenario, which is a primary scenario identified for these mines. Although this approach was not used in this report to evaluate risks, for illustrative purposes the preliminary remediation goals for several scenarios are presented in Table 3.1.

Using the conservative SSG for radionuclides methodology, we have made some estimates of lifetime cancer risk for different exposure time periods and different concentrations for natural uranium, Ra-226, and Th-232. Natural uranium is assumed to include U-234, U-235, and U-238, in natural isotopic abundances. U-238 is in secular equilibrium with its short-lived progeny, U-234 is in secular equilibrium with Th-230, while U-235, Ra-226, and Th-232 are in secular equilibrium with their entire decay chains. The slope factors for natural uranium are expressed in terms of pCi of U-238.[2] Arsenic was evaluated using a similar approach, but using the general SSG (U.S. EPA 1996a and 1996b) methodology.

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[2] For example, the inhalation slope factor (lifetime risk of cancer morbidity per pCi inhaled) for Ra-226 includes the contribution of all of its short- and long-lived progeny. This approach was employed because exposure to airborne radium particles at a mine site would most likely include most of its progeny in equilibrium. This approach slightly overestimates the risks in the case of Ra-226, because the progeny may not be in full equilibrium since some of the Rn-222 may have diffused away. The uranium slope factors do not include Ra-226 and its progeny, because separate SSLs are developed for Ra-226.

Table 3.1. Selected Radionuclide Toxicity and Preliminary Remediation Goals for Superfund for Comparison with the SSG Pathway-Specific Approach

Element and Isotope	Preliminary Remediation Goals (PRGs) (for concentrations above background)			Soil to Groundwater
	Residential Soil (pCi/g)	Agricultural Soil (pCi/g)	Outdoor Worker Soil (pCi/g)	DAF = 20 (pCi/g)
Radium 226 + D	0.012	0.0006	0.026	0.32
Thorium 232	3.1	0.0094	1.9	6.1
Uranium 238 + D	0.74	0.0015	1.8	0.12

D means that decay products are included
DAF is Dilution/Attenuation Factor
Table Source: August 4, 2004 Radionuclide Toxicity and Preliminary Remediation
Goals for Superfund, at http://epa-prgs.ornl.gov/radionuclides/download.shtml.

3.3   Recreational Scenario Risk Calculations

3.3.1   Risk from External Exposure to Radium, Thorium, and Uranium

The SSG methodology assumes a linear relationship between a person's incremental cancer risk from exposure to radium (Ra-226), thorium (Th-232), and natural uranium (U-238 + U-235). The incremental lifetime cancer risk level of 10^{-6} is usually the baseline level of risk that is acceptable, and 5×10^{-4} is typically at the high end of the range of acceptability. Thus the Soil Screening Levels (SSLs) are evaluated for this range.

$$\text{Soil Screening Level (SSL)} = \frac{TR}{SFE * EF/365 * ED * ACF * [ETO + (ETI*GSF)]}$$

where:

TR	=	Target lifetime cancer risk (unitless)	variable $(1 \times 10^{-6} - 5 \times 10^{-4})$
SFE	=	Slope factor for external exposure to soil contaminated	1.23×10^{-5} for Th-232
	=	8.49×10^{-6} for Ra-226	2.14×10^{-7} for U–natural
EF	=	Exposure frequency (days/year)	variable
ED	=	Exposure duration (years);	
		results in risk per total number of days on site	1
		For residential exposure, ED is used to represent the	
		exposure over a number of years, frequently 30 years.	
ACF	=	Area correction factor for smaller sites	
	=	0.9 if area < 1,000 m^2	1
ETO	=	Estimated fraction of time outdoors on site	1
ETI	=	Estimated time indoors	0
GSF	=	Gamma-shielding factor	0

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[3] Includes short- and long-lived decay products, as discussed in preceding section. Slope factors for radionuclides for all exposure pathways are based on U.S. EPA's Health Effects Assessment Summary Tables (HEAST) (http://www.epa.gov/radiation/heast/index.html). The slope factor calculations can be found in Appendix II Calculation of Slope Factors for NORM Decay Series.

Because of the nature of the recreational scenario, some of the typical assumptions have been changed. In the above equation we assume that the person spends the entire day at the site, with no indoor time—that is, the individual spends all day on the waste material and sleeps in a tent or other light structure that provides no appreciable shielding. Since no time is spent indoors, the indoor part of the equation with the gamma shielding does not come into play. For a Superfund target risk of 1×10^{-6} for 14 days of exposure and the assumptions stated above, the Ra-226 soil screening level would be ~3.1 pCi/g (~114 Bq/kg), but for one day of exposure at a 1×10^{-6} target risk, the Ra-226 soil screening level would be ~43 pCi/g (~1,590 Bq/kg). Table 3.2 and Figure 3.2 illustrate the relationship between radium concentration and risk for different times of exposure, Table 3.3 and Figure 3.3 present the corresponding data for exposure to thorium, and Table 3.4 and Figure 3.4 provide similar information for uranium. The relationship is linear, so reducing the estimated time on site by one half (from 100 percent of the time on site to 50 percent) would increase the radium screening level by a factor of two for the same target risk. In addition, if a typical residential exposure duration of 30 years is used, then the values in Table 3.2 and other tables of soil screening levels used in this chapter would need to be divided by 30; however, the assumptions used here (i.e., entire day on the waste material) would not be appropriate for a typical residential scenario. The risk estimated for a recreational exposure could also be used for occupational workers (government workers or contractors for example) who spent time at the site for their jobs.

Table 3.2. Soil Screening Levels for External Exposure to Ra-226

Table 3.2 lists the data used to generate Figure 3.2.

Exposure Frequency (days)	Target Lifetime Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Ra-226 (pCi/g)					
1	21,485	4,297	2,149	430	215	43.0
14	1,535	307	153	30.7	15.3	3.07
30	716	143	72	14.3	7.2	1.43
52	413	83	41.3	8.3	4.13	0.83
140	153	30.7	15.3	3.07	1.53	0.307
350	61.4	12.3	6.14	1.23	0.614	0.123

Figure 3.2. External Exposure - Relationship between Exposure Frequency, Radium Concentration, and Target Lifetime Cancer Risk

Figure 3.2 is derived from Table 3.2. The x-axis is the activity concentration of radium in the uranium mine waste material, and the y-axis is the incremental lifetime cancer risk as a result of exposure from the radium in the waste material for different time periods. For example, exposure to 12.3 pCi/g (454 Bq/kg) of radium, in secular equilibrium with its progeny, for 350 days, would result in a lifetime cancer risk of 10^{-4}
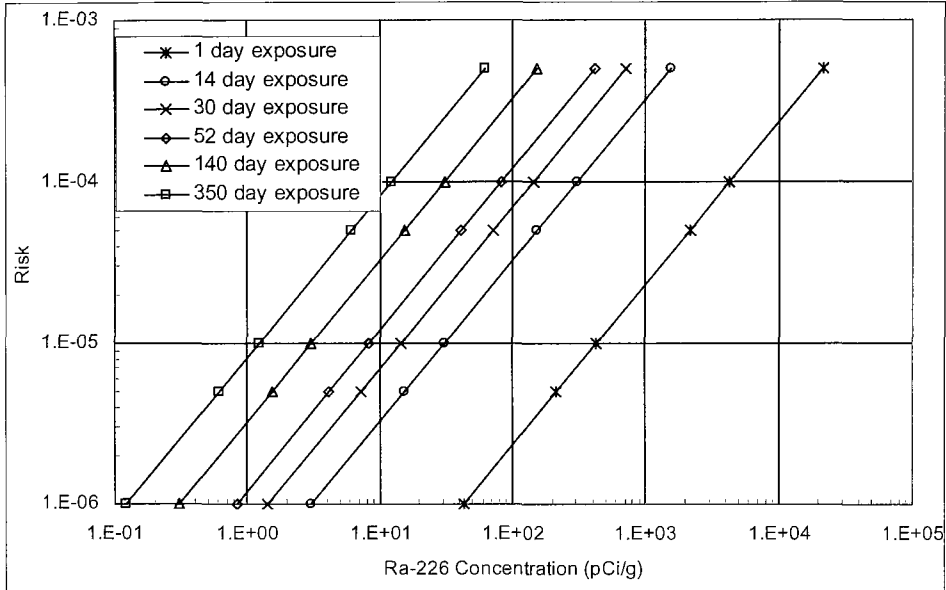
Table 3.3. Soil Screening Levels for External Exposure to Th-232

Table 3.3 lists the data used to generate Figure 3.3

Exposure Frequency (days)	Target LifetimeCancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Th-232 (pCi/g)					
1	14,849	2,970	1,485	297	148	29.7
14	1,061	212	106	21.2	10.6	2.12
30	495	99	49.5	9.9	4.95	0.99
52	286	57	28.6	5.71	2.86	0.571
140	106	21.2	10.6	2.12	1.06	0.212
350	42.4	8.5	4.24	0.85	0.424	0.085

Figure 3.3. External Exposure - Relationship between Exposure Frequency, Thorium Concentration, and Target Lifetime Cancer Risk

Figure 3.3 is derived from Table 3.3. The x-axis is the activity concentration of thorium in the uranium mine waste material, and the y-axis is the incremental lifetime cancer risk as a result of external exposure to the thorium in the waste material for different time periods. For example, exposure to 8.5 pCi/g (314 Bq/kg) of Th-232, in secular equilibrium with its progeny, for 350 days, would result in a cancer risk of 10^{-4}.
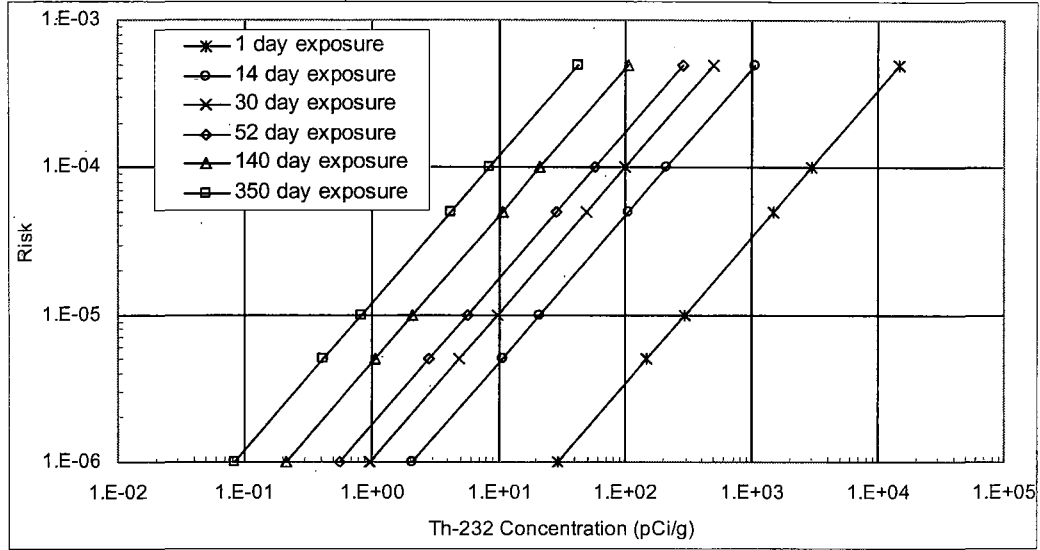
Table 3.4. Soil Screening Levels for External Exposure to Natural Uranium

Table 3.4 lists the data used to generate Figure 3.4

Exposure Frequency (days)	Target Lifetime Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Natural Uranium (pCi/g U-238)					
1	852,189	170,438	85,219	17,044	8,522	1,704
14	60,871	12,174	6,087	1,217	609	122
30	28,406	5,681	2,841	568	284	56.8
52	16,388	3,278	1,639	328	164	32.8
140	6,087	1,217	609	122	60.9	12.2
350	2,435	487	243	48.7	24.3	4.87

Figure 3.4. External Exposure - Relationship between Exposure Frequency, Uranium Concentration, and Target Lifetime Cancer Risk

Figure 3.4 is derived from Table 3.4. The x-axis is the activity concentration of U-238 in the uranium mine waste material, and the y-axis is the incremental lifetime cancer risk as a result of exposure to uranium in the waste material for different time periods. For example, 350 days of exposure on site to 487 pCi/g (18,020 Bq/kg) of U-238, in secular equilibrium with its progeny, as well as U-235 in the ratio of natural abundance (see discussion of uranium progenies earlier in this chapter) would result in a lifetime cancer risk of 10^{-4}
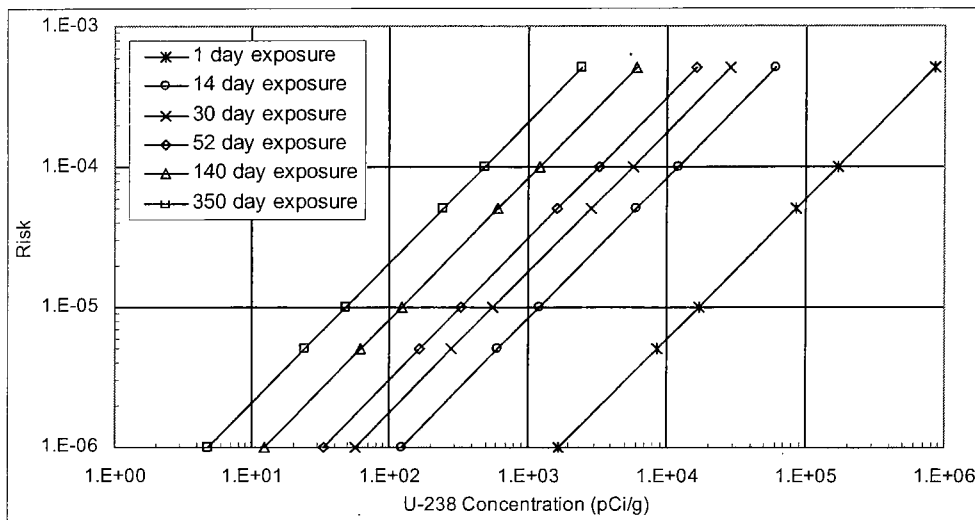
3.3.2 Risk from Soil Ingestion

While the direct ingestion of soil is possible at a site, it is not likely to be a major exposure pathway for adults. The following equation uses an age-adjusted soil ingestion factor to account for the fact that children have a higher intake of soil than adults (U.S. EPA 2000b).

$$SSL = \frac{TR}{SFs * IRs * 1 \times 10^{-3} * EF * ED}$$

where:

TR	=	Target lifetime cancer risk (unitless)
SF_S	=	Soil ingestion slope factor $(pCi)^{-1}$
		Ra-226 = 3.39×10^{-9}
		Th-232 = 3.33×10^{-9}
		U-natural = 6.48×10^{-10}
IR_S	=	Soil ingestion rate (120 mg/day)
1×10^{-3}	=	Conversion factor (g/mg)
EF	=	Exposure frequency (variable)
ED	=	Exposure duration (1 year)

Sample calculation for radium, assuming a target lifetime risk of 1×10^{-6} and exposure for 14 days:

$$SSL = 1 \times 10^{-6} \div (3.39 \times 10^{-9} * 120 * 1 \times 10^{-3} * 14 * 1) = 176 \text{ pCi/g } (\sim 6,500 \text{ Bq/kg})$$

Table 3.5. Soil Screening Levels for Ingestion of Ra-226 in Soil

Exposure Frequency (days)	Target Lifetime Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Ra-226 (pCi/g)					
1	1.23E+06	2.46E+05	1.23E+05	2.46E+04	1.23E+04	2.46E+03
14	8.78E+04	1.76E+04	8.78E+03	1.76E+03	8.78E+02	1.76E+02
30	4.10E+04	8.19E+03	4.10E+03	8.19E+02	4.10E+02	8.19E+01
52	2.36E+04	4.73E+03	2.36E+03	4.73E+02	2.36E+02	4.73E+01
140	8.78E+03	1.76E+03	8.78E+02	1.76E+02	8.78E+01	1.76E+01
350	3.51E+03	7.02E+02	3.51E+02	7.02E+01	3.51E+01	7.02E+00

Figure 3.5. Relationship between Exposure Frequency, Radium Concentration, and Target Lifetime Cancer Risk from Soil Ingestion

Figure 3.5 is derived from Table 3.5. The x-axis is the activity concentration of Ra-226 in the uranium mine waste material, and the y-axis is the incremental lifetime cancer risk as a result of ingestion of radium in the waste material for different exposure times.
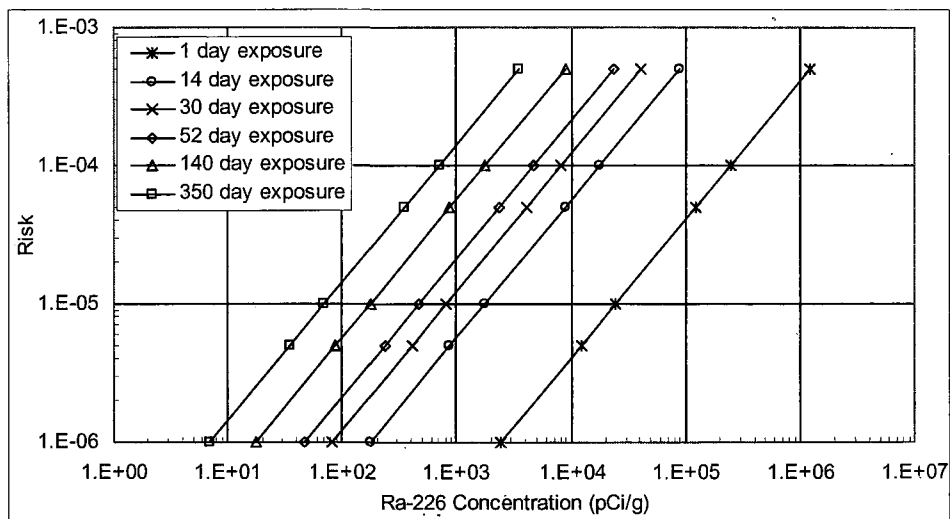
Table 3.6. Soil Screening Levels for Ingestion of Th-232 in Soil

Exposure Frequency (days)	Target Lifetime Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Th-232 (pCi/g)					
1	1.25E+06	2.50E+05	1.25E+05	2.50E+04	1.25E+04	2.50E+03
14	8.94E+04	1.79E+04	8.94E+03	1.79E+03	8.94E+02	1.79E+02
30	4.17E+04	8.34E+03	4.17E+03	8.34E+02	4.17E+02	8.34E+01
52	2.41E+04	4.81E+03	2.41E+03	4.81E+02	2.41E+02	4.81E+01
140	8.94E+03	1.79E+03	8.94E+02	1.79E+02	8.94E+01	1.79E+01
350	3.58E+03	7.15E+02	3.58E+02	7.15E+01	3.58E+01	7.15E+00

Figure 3.6. Relationship between Exposure Frequency, Thorium Concentration, and Target Lifetime Cancer Risk for Soil Ingestion

Figure 3.6 is derived from Table 3.6. The x-axis is the activity concentration of thorium in the uranium mine waste material, and the y-axis is the incremental lifetime cancer risk as a result of ingestion of thorium in the waste material for different exposure times.
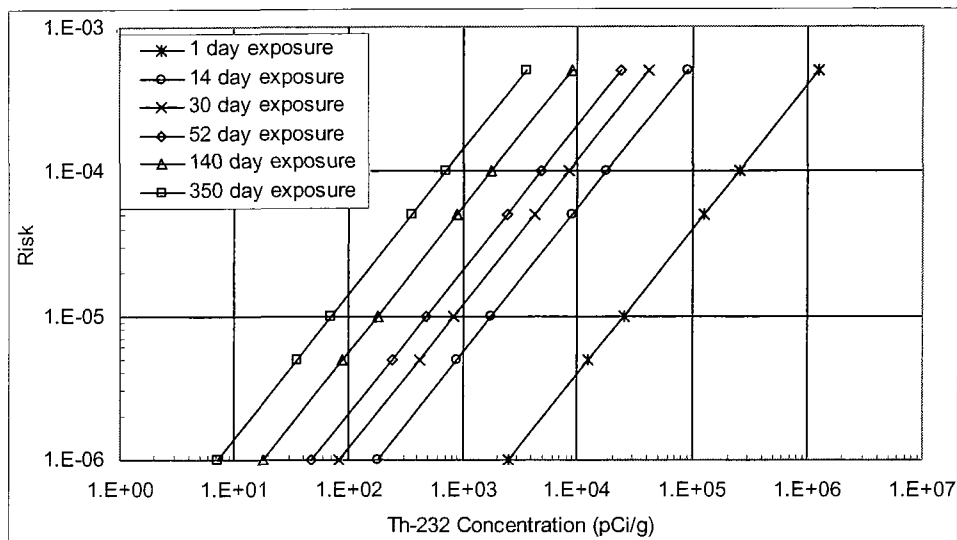
Table 3.7. Soil Screening Levels for Ingestion of Natural Uranium in Soil

Exposure Frequency (days)	Target Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Natural Uranium (pCi/g U-238)					
1	6.43E+06	1.29E+06	6.43E+05	1.29E+05	6.43E+04	1.29E+04
14	4.59E+05	9.18E+04	4.59E+04	9.18E+03	4.59E+03	9.18E+02
30	2.14E+05	4.29E+04	2.14E+04	4.29E+03	2.14E+03	4.29E+02
52	1.24E+05	2.47E+04 ·	1.24E+04	2.47E+03	1.24E+03	2.47E+02
140	4.59E+04	9.18E+03	4.59E+03	9.18E+02	4.59E+02	9.18E+01
350	1.84E+04	3.67E+03	1.84E+03	3.67E+02	1.84E+02	3.67E+01

Figure 3.7. Relationship between Exposure Frequency, Uranium Concentration, and Target Lifetime Cancer Risk from Soil Ingestion

Figure 3.7 is derived from Table 3.7. The x-axis is the activity concentration of U-238 in the uranium mine waste material, and the y-axis is the incremental cancer risk as a result of ingestion of uranium in the waste material for different exposure times.
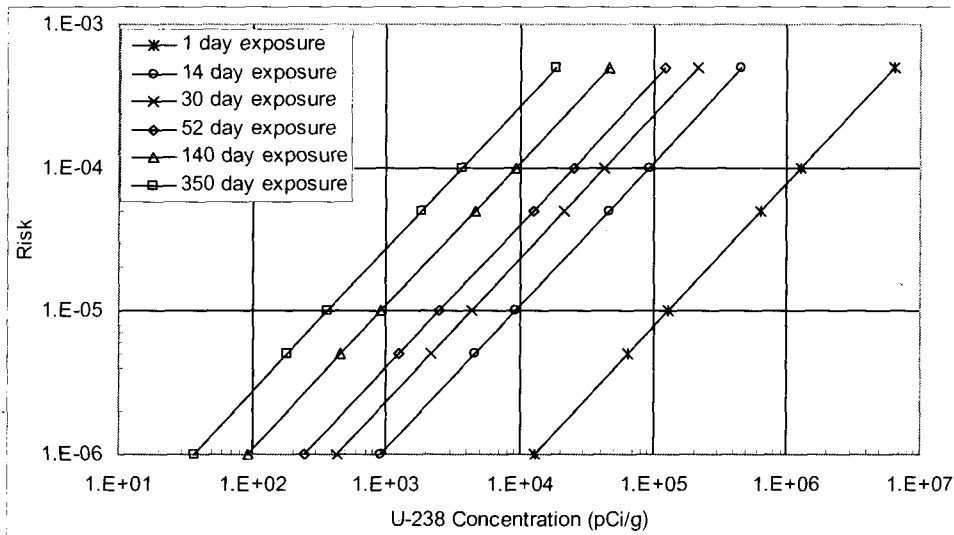

3.3.3 Risk from Inhalation of Radium, Thorium, and Uranium in Fugitive Dust

Windblown dust provides a pathway for radioactive materials to reach humans through inhalation. The equation for inhalation from the Superfund SSG (EPA 2000b) is:

$$SSL = \frac{TR}{SF_I * IR_I * (1/PEF) * 1 \times 10^3 * EF * ED * [ETO + (ETI * DFI)]}$$

where:

TR	=	Target lifetime cancer risk (unitless)	10^{-6}
			2.55×10^{-8} Ra-226
SF_I	=	Inhalation Slope Factor (pCi^{-1})	1.92×10^{-7} Th-232
			6.14×10^{-8} U-natural
IR_I	=	Inhalation Rate (m^3/day)	20
PEF	=	Particulate Emission Factor (m^3/kg)	1.32×10^9
1×10^3	=	Conversion factor (g/kg)	–
EF	=	Exposure frequency (days/ year)	350
ED	=	Exposure duration (year)	1
ETO	=	Exposure time fraction, outdoor (unitless)	1
ETI	=	Exposure time fraction, indoor (unitless)	0
DFI	=	Dilution factor for indoor inhalation (unitless)	NA

Using these parameters, the 350-day SSL for Ra-226 is 7,395 pCi/g (2.74×10^5 Bq/kg), 985 pCi/g (3.64×10^4 Bq/kg) for Th-232, and 3,070 pCi/g (1.14×10^5 Bq/kg) for natural uranium. This applies to exposed individuals in the vicinity of the mine.

3.3.4 Risk from Use of All-Terrain Vehicles (ATVs)

The recreational use of ATVs and dirt bikes in the western United States is very common. These vehicles allow easy access to very remote areas, so the safety provided by a mine's remote location is often negated. The soil screening levels for inhalation of dust resuspended during the operation of ATVs are estimated from empirical data on emission of dust from unpaved roads. A scoping scenario for this pathway was developed, as described below.

It is assumed that a rider of an ATV or other off-road recreational vehicle riders would participate in the sport about 60 times a year (once a week plus additional days on vacations or holidays). It is further assumed that an abandoned mine site would lie on his route, and that he would cross the site twice on each ride, going and returning over the same route. The area of the site is 463.5 hectares (ha), the average of the total disturbed areas of the 21 mines listed in DOE/EIA 2000b, Appendix C. This is a bounding condition as the estimated size of an abandoned mine is expected to be much less, on the order of two hectares (U.S. EPA 2006a). The area is assumed to be circular, and the route to be along the diameter of the circle. The riders have inhalation rates of 1.2 m³/h, the average rate for light activity. The vehicles travel at an average speed of 40 mph. The airborne concentration of respirable dust, 5 mg/m³, is based on the average of three measured dust concentrations at a height of 2 m taken at the side of a road composed of dirt and crushed slag, during the passage of medium-duty vehicles (3–4 tons) traveling at a speed of 15 mph (Cowherd et al. 1979). The dust had a mass-median diameter of 10–11 μm, and thus corresponds to the approximate range of respirable particles. As it happens, this concentration is also equal to the OSHA protective exposure limit (PEL) for nuisance dust set forth in 29 CFR 1910.1000, and thus constitutes a reasonable upper bound to the average dust loadings that could be comfortably tolerated by the rider. The SSLs are calculated using the preceding equation for inhalation of contaminated dust. The parameters that were changed for the ATV scenario are presented below.

The daily inhalation rate of the rider while exposed to the dust on the mine site is calculated as follows:

$$IR_1 = \frac{I_h \, 4 \sqrt{\dfrac{A_s}{\pi}}}{v}$$

where:

IR_1	=	inhalation rate during exposure(m³/d)	=	0.0906
I_h	=	inhalation rate for light activity(m³/h)	=	1.2
A_s	=	Area of site (m²)	=	4.635×10^6
v	=	speed of vehicle(40 mi/h)	=	64,374 m/h

The emission factor is simply the reciprocal of the dust loading, and is evaluated as follows:

PEF   =   emission factor
               = $1/\chi$ = 0.2 m³/mg   = 2×10^5 m³/kg
               χ =   concentration of respirable dust   =   5 mg/m³

EF   =   Exposure frequency   =   60 d/y

ETO   =   Exposure time fraction, outdoor   =   1

Based on these values, the SSLs calculated for this scenario are:

	Soil Screening Level	
Radionuclide	pCi/g	Bq/kg
Ra-226	1,445	5.35E+04
Th-232	192	7.12E+03
U-natural	600	2.22E+04

3.4   Other Recreational Use Scenarios

Other recreational use scenarios were considered as part of the present analysis. These include swimming, boating, fishing, and hunting, along with the consumption of on-site fish and game. These scenarios are either unlikely to occur, or would be an insignificant component of the risk, as reviewed in an EPA study (1983b). This study addressed related scenarios for nearby residents [within 1 mile (1.6 km)] of the mines, including cattle grazing and crop ingestion, as discussed below.

Although the pit lake at the Yazzie-312 Mine was used for swimming by local residents, the lake was drained and filled in as part of the remediation of the mine site after 40 years of abandonment. The number of other abandoned uranium mines with pit lakes is unknown. However, swimming, through water immersion and ingestion pathways, contributes little total dose (< 10 mrem or < 10^{-1} mSv) or risk. Estimates of risk from swimming are provided in Appendix 1. Fishing is not considered in this analysis. Pit lakes, being artificial and not connected to any natural bodies of water, are assumed to be devoid of fish or expected to contain minimal fish populations.

The majority of mine sites found in the uranium location database are typically in an arid environment that does not readily support plant life unless irrigated. In such arid environments, the overburden or protore piles are not expected to be able to provide much forage for animals, especially if they are covered with a desert varnish. In addition, the size of the abandoned mine sites would typically be relatively small and thus provide little forage for game animals. Consequently, any game taken on a mine site would be expected to have obtained most of its forage elsewhere. The meat from such game is thus not expected to be significantly contaminated with TENORM from a mine site.

3.5   Metals in Uranium Mines

Metals and other minerals of commercial value frequently occur in the same ore deposits with uranium (See Volume I, Chapters I and II, U.S.EPA 2006a) and, in some cases, it is economical to mine them together. The most common commodities associated with uranium in the BASINS

MAS/MILS (Mineral Availability System/Mineral Industry Location System) database are phosphate, vanadium, gold, and copper. U.S. EPA (1999) provided an extensive review of TENORM contamination, including uranium, associated with copper mines in Arizona. However, numerous other commodities are associated with uranium, including antimony, molybdenum, fluorine, rare earths, thorium, lead, mica, tantalum, and beryllium. For example, in Colorado, 83 of 2,304 records had gold associated with uranium, and 10 had silver as a secondary commodity; 38 records listing vanadium as a primary commodity also listed uranium as a secondary commodity; and vanadium was listed as the primary or secondary commodity with uranium in over 2,000 of the records. While multiple metals are associated with uranium mines, limited information is available to determine the concentrations of the metals at the different sites.

The 1983 EPA report to Congress indicated that at uranium mines, no adverse effects were expected from nonradiological constituents because of the low airborne concentrations, with the exception of fugitive dusts from operating mines (U.S. EPA 1983a, b, and c). Nevertheless, mining in general in the West has been known to generate problems with heavy metal contamination in sediments and water, and some mines are Superfund sites (U.S. EPA 2001d).

3.5.1 Risk from Exposure to Arsenic

Arsenic, a carcinogen, is a metal of special concern. This naturally occurring metal may be a common contaminant in uranium mine wastes. The presence of arsenic in extremely high amounts in soils, as well as in the water, posed a significant risk at the White King/Lucky Lass uranium mines. In the study (Portage Environmental 2005) of the Riley Pass Uranium Mines in Harding County, South Dakota, arsenic was considered to be "the primary risk driver." The primary exposure scenario at that site also involved recreational users of the site. The following equation is used to estimate the lifetime cancer risk from ingestion of arsenic:

$$\text{Arsenic SSL} = \frac{TR * AT * 365}{SF_O * 10^{-6} * EF * IF_{soil/adj}}$$

where:

TR	=	Target lifetime cancer risk	Variable
AT	=	Averaging time (years)	70
SF_O	=	Slope factor for arsenic $(mg/kg\text{-}d)^{-1}$	1.5
EF	=	Exposure frequency (days/year)	Variable
365	=	Conversion factor (days/y)	
10^{-6}	=	Conversion factor (kg/mg)	

$IF_{soil/adj}$ is the ingestion factor (age-adjusted), in units of mg y kg^{-1} d^{-1}. Because the recreational use of the mine site is assumed to be episodic—it would occur for a limited period of time during a given year—the limiting exposure would be to a child.[4] Employing the data for a child, 0 – 6

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[4] The risks to a child were calculated for this chemical carcinogen because the expression for the ingestion factor is age dependent. This is unlike the calculation of risks from radionuclides, where the reference slope factors calculated by EPA are age adjusted.

years old, the ingestion factor is given by the following expression, modified from the expression for the residential scenario in U.S. EPA 1996b:

$$IF_{soil/age\ 1-6} = \frac{IR_{soil/age\ 1-6}}{BW_{age\ 1-6}}$$

where:

$IR_{soil/age\ 1-6}$	=	soil ingestion rate of child (mg/d)	200
$BW_{age\ 1-6}$	=	body weight of child (kg)	15

The results are presented in Table 3.8. For a target lifetime risk of 5×10^{-5} and an exposure of 7 days/year, the arsenic soil screening level for children would be ~8,250 mg/kg. The lowest SSL is 3 mg/kg for the 350-day exposure at 1×10^{-6} target risk. For perspective, for the White King/Lucky Lass Superfund site, arsenic concentrations in surface soil were 769 mg/kg and 12 mg/kg, respectively, while background arsenic soil concentrations in the area were ~4 mg/kg. The Riley Pass Uranium Mines arsenic average concentrations were over 500 mg/g (Portage Environmental 2005). Although an occasional visitor to these sites does not incur much risk from arsenic, it could pose a problem for those who frequent the sites.

Table 3.8. Target Lifetime Cancer Risk for Ingestion of Arsenic by Children Up to 6 Years Old

Exposure Frequency (days/year)	Target Lifetime Cancer Risk					
	5×10^{-5}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Soil Screening Level for Arsenic (mg/kg)					
1	638,750	115,387	57,694	11,539	5,769	1,154
5	115,387	23,077	11,539	2,308	1,154	231
7	82,419	16,484	8,242	1,648	824	165
14	41,210	8,242	4,121	824	412	82
350	1,648	330	165	33	16	3

3.5.2 Risk from Drinking Mine-Contaminated Water

In addition to their potential to pose health risks on the site, uranium mines and their wastes can affect surface or groundwater. For example, the pond in the mining pit could be contaminated with radionuclides or metals, which would make the pond an exposure pathway. In addition, the overburden (or protore) waste materials could leach into the ground and move into the groundwater below. Material could also be physically transported from the waste piles by runoff or wind (see discussion and data on theYazzie-312 Mine in Volume I, Chapter 3, U.S. EPA 2006a). In another scenario, the mine workings could intersect and contaminate groundwater.

There are multiple scenarios in which people could drink water contaminated from unreclaimed uranium mining operations. For a recreational user of the site, the exposure may be short-term from a spring, stream, or pond. Others could have lifetime exposure due to proximity to a uranium mine. Also, someone who does not live on contaminated property could be exposed to radionuclides from communal wells, which occurs on the Navajo Reservation in the Four

Corners area (U.S. EPA and USACE 2000). The radionuclides in groundwater can be due to contamination from mining activities or from high natural background sources, including the uranium ore body exploited by the mining operation. However, many large uranium mining operations have reported problems of groundwater contamination (U.S. DOE/EIA 2000b, Appendix C).

EPA's 1983 Report to Congress studied concentrations in, and risks from, waters discharged from active mines to surface waters. The authors estimated that an insignificant health risk accrues to populations from waterborne radionuclides due to water discharges from an average existing active mine (U.S. EPA 1983b). However, the report acknowledged that some abandoned underground mines were probably discharging contaminated waters into streams and shallow aquifers, and the data were insufficient to determine the health risks from drinking the water. Furthermore, due to a lack of data, the authors could not determine the health hazard to individuals who drink from contaminated surface or underground sources. However, Volume I of this study (U.S. EPA 2006a) reports on concentrations of radionuclides in ponds and streams associated with open pit uranium mines, and case studies where shallow groundwater and surface springs or streams were contaminated by uranium mine discharges.

EPA has established maximum contaminant levels (MCLs) for several radionuclides in community water supplies that serve more than 25 customers (Table 3.9). These MCLs can be used to help establish soil cleanup levels at a site. The SSG approach is used to conservatively identify a soil level that would prevent a site contaminant from attaining the MCL in groundwater. The drinking water MCL for uranium is based primarily on kidney toxicity, rather than radiological effects.

Table 3.9. Radionuclide Maximum Contaminant Levels for Public Water Supplies

EPA has established drinking-water maximum contaminant levels for several radionuclides. Although these values are for public water supplies, the Superfund program has applied them to site cleanups.

Radionuclide	Maximum Contaminant Level
Uranium	30 μg/L
Man-made beta/photon emitters	4 mrem/y (0.04 mSv/y) to whole body or any organ
Alpha emitters (excluding radon and uranium)	15 pCi/L (555 Bq/m^3)
Combined radium-226 and radium-228	5 pCi/L (185 Bq/m^3)

Source: Modified from EPA 2000c.

While the number of people who drink water contaminated by uranium mining activities is unknown, it is possible to calculate an individual lifetime risk for various concentrations of radionuclides. The numbers in Table 3.10 are based on the risk calculations presented in the technical support document for the radionuclides in drinking-water regulation (U.S. EPA 2000d).

Table 3.10. Radionuclide Mortality and Morbidity Risk Coefficients[5]

While the number of people who drink water contaminated by uranium mining activities is unknown, it is possible to calculate an individual lifetime risk for various concentrations of radionuclides.

Radionuclide	Mortality Risk Coefficient per pCi Consumed	Morbidity Risk Coefficient per pCi Consumed
Radium[a]	5.66×10^{-10}	8.03×10^{-10}
Th-232[b]	6.92×10^{-11}	1.01×10^{-10}
Ra-228[b]	7.40×10^{-10}	1.04×10^{-9}
Th-228[b]	6.73×10^{-11}	1.07×10^{-10}
Ra-224[b]	1.01×10^{-10}	1.67×10^{-10}
Uranium[c]	4.4×10^{-11}	6.81×10^{-11}
Gross alpha[d]	1.14×10^{-10}	1.83×10^{-10}

[a]   Average weighted by relative prevalence of Ra-226 and Ra-228
[b]   Principal members of Th-232 decay chain
[c]   Arithmetic average for natural uranium isotopes: U-234, U-235, U-238
[d]   Average weighted by relative prevalence of Ra-224 and Ra-226
Source: U.S. EPA 2000d.

The equation used to calculate the risks from these radionuclides is:

Risk = Concentration (pCi/L) * Risk coefficient * Water consumed (L/day) * Exposure frequency (days/year) * Number of years

Figures 3.8–3.10 depict the risks from radium, gross alpha, and uranium for (1) 70 years of exposure, 365 days a year, drinking 2 liters of water a day from the contaminated source, representing lifelong consumption; and (2) 10 years of exposure, 14 days a year, drinking 2 liters a day, representing recreational consumption. For the first situation, long-term exposure produces risks of up to 1×10^{-3} for some of the higher concentrations. However, for the long-term recreational user consuming contaminated water, the lifetime risk remains less than 6×10^{-6}.

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[5] Morbidity risk is the risk of getting cancer, and mortality risk is the risk of dying from cancer.

Figure 3.8. Cancer Risks from Lifetime and Recreational Exposures to Radium in Drinking Water: 70 Years, 365 Days/Year & 10 Years, 14 Days/Year Exposure

Long-term exposure to radionuclide-contaminated water produces risks of up to 1×10^{-3} for some of the higher concentrations. However, the risk from long-term recreational consumption is less than 6×10^{-6}
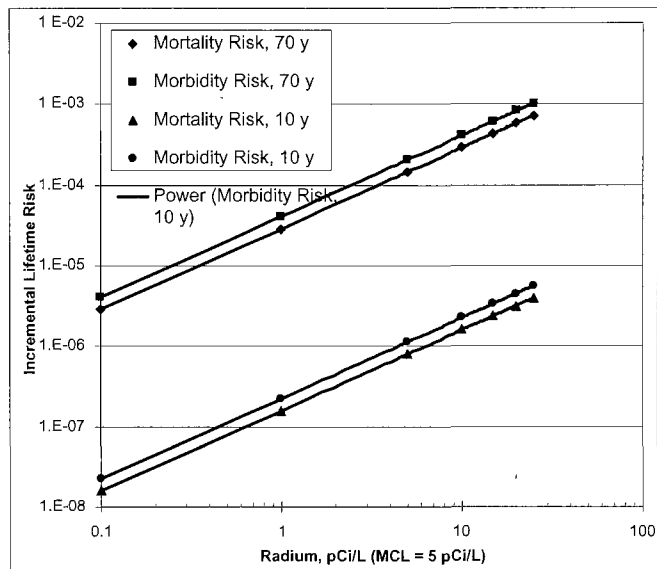
Figure 3.9. Cancer Risks from Lifetime and Recreational Exposures to Gross Alpha in Drinking Water: 70 Years, 365 Days/Year & 10 Years, 14 Days/Year Exposure

Long-term exposure to radionuclide-contaminated water produces risks of up to 1×10^{-3} for some of the higher concentrations. However, the risk from long-term recreational consumption is less than 6×10^{-6}
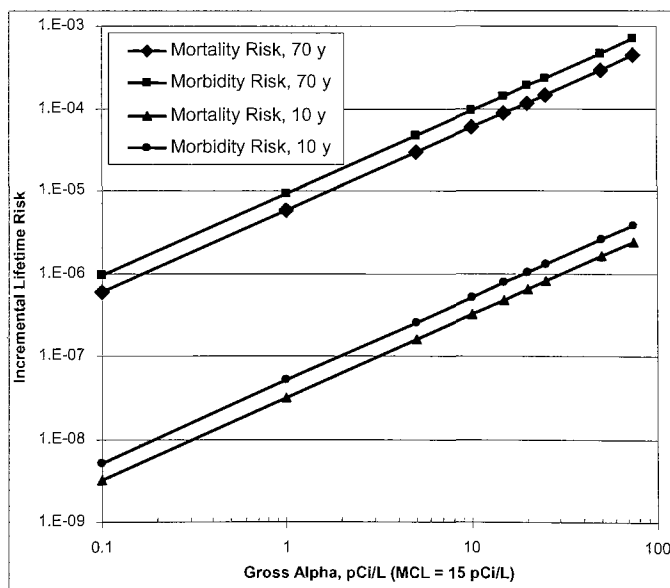
**Figure 3.10. Cancer Risks from Lifetime and Recreational Exposures
to Uranium in Drinking Water:
70 Years, 365 Days/Year and 10 Years 14 Days/Year Exposure**

*Long-term exposure to radionuclide-contaminated water produces risks of up
to 1 × 10⁻³ for some of the higher concentrations. However, the risk from
long-term recreational consumption is less than 6 × 10⁻⁶*
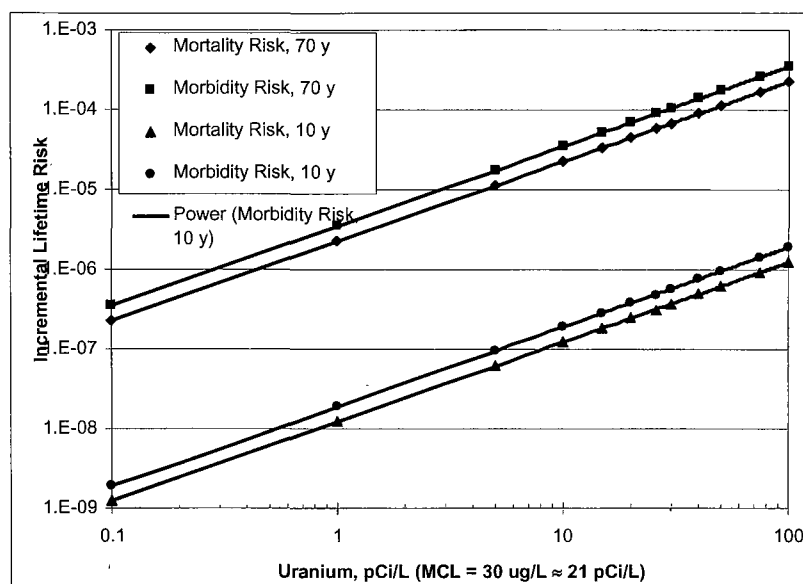
Table 3.11 estimates the potential lifetime cancer risk from radionuclides in the shallow Yazzie-312 Mine pit water (Panacea 2002), at concentrations measured before the pit was remediated. At these levels, long-term consumption of drinking water containing the radionuclides would be a significant health risk, but shorter-term exposures would not.

**Table 3.11. Lifetime Risks Estimated from Drinking Unremediated
Yazzie-312 Mine Pit Water**

*While long-term consumption of drinking pit water from the Yazzie-312 Mine
posed a significant health risk, shorter-term exposures would not.*

Contaminant	Average Concentration	Exposure Duration			
		70 Years, 365 Days/Year		10 Years, 14 Days/Year	
		Mortality	Morbidity	Mortality	Morbidity
Total Radium	2.3 pCi/L	7×10^{-5}	9×10^{-5}	4×10^{-7}	5×10^{-7}
Total Uranium	173 pCi/L	4×10^{-4}	6×10^{-4}	2×10^{-6}	3×10^{-6}
Gross alpha[a]	84 pCi/L	5×10^{-4}	8×10^{-4}	3×10^{-6}	4×10^{-6}
Total Risk	--	9.7×10^{-4}	1.5×10^{-4}	5.4×10^{-6}	7.5×10^{-6}

[a] Without uranium and radon

Note: Other periods of exposure may be of interest, such as a 30-year period, often used in Superfund calculations. Since the relationship between concentration and risk is linear, a ratio can be used to calculate risks at different time periods. To estimate the risk for 30 years of exposure, divide the 70-year risk number by 2.33 (70 y/30 y). Arsenic was measured in the pit at

an average concentration of 55 µg/L, just over the MCL in effect in 2005 and five times higher than the 10 µg/L MCL that became effective in 2006. In calculating the risk from arsenic in the water, the following equation and defaults from Superfund Risk Assessment Guidance (U.S.EPA 1989b) were used:

Target lifetime cancer risk, TR = (SF$_O$ * C * IRW * EF * ED) / (BW * AT * 365 days/year)

where:

SF$_O$	=	Slope factor for arsenic (mg/kg-d)$^{-1}$	1.5
C	=	Pit water arsenic concentration (mg/L)	0.055
IRW	=	Daily water ingestion rate (L/day)	2
EF	=	Exposure frequency (days/y)	350
ED	=	Exposure duration (years)	30
BW	=	Body weight (kg)	70
AT	=	Averaging time (years)	70

Using the default values listed above, we estimate the risk for drinking arsenic to be about 1 in 1,000, assuming 30 years of exposure (1.5 * 0.055 * 2 * 350 * 30 /[70 * 70 * 365] = 1,732.5 / 1,788,500 = 9.7 × 10^{-4} ~ = 1 × 10^{-3}). For an exposure of 14 days/year for 10 years, the risk estimate is 1.3 × 10^{-5} or ~ = 1 × 10^{-5}. Thus, the pit water at the Yazzie-312 Mine could have posed a high risk from both radionuclides and arsenic, if the water were consumed over long periods of time.

The 1983 EPA report to Congress also reported Wyoming and New Mexico field studies of trace elements and radionuclides from inactive mining areas at off-site locations (U.S. EPA 1983c). In both cases, precipitation is seasonal and adjacent streams are dry much of the year. The general observations were that concentrations of Ra-226 and U-238 from spoils piles and in stream channels decreased rapidly with distance from the mines. However, the migration of trace metals did not show as distinct a trend. The transport processes were believed to be wind erosion and sheet erosion from cloudbursts, and they appeared to move mine spoils material up to 2,000 feet (~600 m) in 10 years. Preliminary data from recent sampling by Burghardt (2003) at several uranium mines have identified decreasing uranium and arsenic concentrations from the toe of the pile to background levels within several hundred meters.

3.6   Migration of Uranium Waste into Groundwater

Chemical and physical processes can enhance or retard the movement of the contaminants into and through an aquifer. Infiltration of water into soil is an example of a physical process, while partitioning of the contaminant between the soil and water is an important chemical process (which gives rise to the soil–water distribution coefficient, K$_d$). On the Colorado Plateau, where many uranium mines are located, the dry climate limits the available water for transporting the radionuclides and for drinking. Much of the precipitation is lost to evapotranspiration, thus limiting the infiltration, although high intensity precipitation events may contribute to increased infiltration at times. In large parts of the Colorado Plateau, the only usable water available in quantity is from groundwater (U.S. EPA 1983b), particularly in relatively deep confined aquifers, but near-surface aquifers are present in some areas. The impact of small surface

uranium mines on most of the groundwater in this region is expected to be minimal. As an example described in more detail below, drilling and sample analysis of a groundwater aquifer located under the Yazzie-312 pit lake found no direct communication or correlation of water chemistry with the overlying lake (Panacea 2002). However, underground mines that intersect an aquifer could contaminate the aquifer, as could large surface mines with deep pits. Also, in areas with greater precipitation or near-surface unconfined aquifers, including higher elevations in the Colorado Plateau, contaminated water may more easily reach the groundwater, where it could be transported and pose significant cancer risks to people who obtain their drinking water from the aquifer.

3.7   Mobility of Uranium and Radium through Groundwater

EPA's *Soil Screening Guidance for Radionuclides* is one method that can be used to conservatively estimate the potential for a radionuclide to move into groundwater and to develop a general understanding of the resulting health risks (U.S. EPA 1996a, 2000b). This approach, which is modified as site-specific conditions are understood, relies on the use of distribution coefficients. This generalized approach is useful for this scoping analysis, since many potentially different site conditions and parameters would need to be considered otherwise. Indeed, for an individual site it is important to gather site-specific information before decisions are made for the particular site. A goal in establishing a soil contaminant concentration is to avoid future contamination of groundwater above the maximum concentration level (MCL) established for the contaminant in potable water. This general approach is also applicable to metals, but the focus here is on key radionuclides.

In calculating the SSL, in pCi/g, for groundwater the equation is:[6]

$$C_t = C_w * (1 \times 10^{-3}) * (K_d + \theta_w/\rho_b)$$

where:

C_t	=	Total concentration in soil (pCi/g)	1.5
C_w	=	Target concentration in leachate (pCi/L)	element-specific, ~20 pCi/L for uranium
1×10^{-3}	=	Conversion factor (kg/g)	
K_d	=	Soil-water partition coefficient (mL/g)	Element-specific
θ_w	=	Water-filled porosity (unitless)	0.3
ρ_b	=	Dry soil bulk density (kg/L)	1.5

C_w, the target concentration in the leachate, is derived by multiplying the MCL by a dilution factor of 20[7], the soil-water partition coefficient is specific to the contaminant of concern, and default values are used for the unitless water-filled porosity, and the dry soil bulk density (U.S. EPA 2000b, Equation 6).

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[6] There are additional variations on this equation, including a mass-limit version that includes infiltration. More detail on this and alternative ground-water transport models are discussed in the EPA Soil Screening Guidance Technical Background Document (U.S. EPA 1996b).

[7] Default value from U.S. EPA 1996b, Part 2.

The SSL generally corresponds to a risk of 1×10^{-6}, and the actual cleanup goal is modified from there; however, for groundwater it is based on achieving the MCL. Tables 3.13 and 3.15 provide the soil screening levels for uranium and radium, respectively, assuming varying soil-water partition coefficients with the target concentration as the MCL. Thus, $C_w = 600$ µg/L of uranium for an MCL of 30 µg/L [or ~20 pCi/L using the uranium specific conversion 0.67 pCi/µg (U.S. EPA 2000d)].

In using this equation, it is important to note the following simplifying assumptions applied in the Soil Screening Guidance methodology. The assumption that soil contamination extends from the surface to the water table adds a conservative element to the equations, since this condition would be uncommon in the Colorado Plateau, where the depth to water can be tens of meters or more, precipitation is limited, and the aquifer is typically confined. However, in other areas where water is near the surface, this list of simplifying assumptions may not be as conservative.

Simplifying Assumptions for the Migration of Radionuclides to Groundwater

- The source is infinite (i.e., steady-state concentrations will be maintained in groundwater).

- Contaminants are uniformly distributed throughout the zone of contamination.

- Soil contamination extends from the surface to the water table (i.e., adsorption sites are filled in the unsaturated zone beneath the area of contamination).

- There is no chemical or biological degradation in the unsaturated zone.

- Equations do not account for radioactive decay.

- Equilibrium soil/water partitioning is instantaneous and linear in the contaminated soil.

- The receptor well is at the edge of the source (i.e., there is no dilution from recharge downgradient of the site) and is screened within the plume.

- The aquifer is unconsolidated and unconfined (surficial).

- Aquifer properties are homogeneous and isotropic.

- Chelating or complexing agents are not present.

- No facilitated transport (e.g., colloidal transport) of inorganic contaminants occurs in the aquifer.

Source: U.S. EPA 2000b.

3.7.1 *Uranium*

Depending on the environmental conditions, uranium can be mobile enough to leach into and move through groundwater, especially in the oxidizing conditions at low pH levels that are present in acid mine drainage. Uranium tends to be relatively immobile under reducing conditions. Table 3.12 illustrates the range of uranium mobility as a function of pH, and Table 3.13 indicates the soil screening level above background needed to achieve the MCL of 30 µg/L. A higher partition coefficient (K_d) means that the movement of uranium would be slower relative

to the movement of water. In the White King monitoring wells, the ore pile area pH was between 4.2 and 6.9, the mine spoil area pH was between 5.6 and 7.0, and the pH in unaffected areas in the vicinity was between 6.3 and 7.7 (USFS 1991).

Although no K_ds were calculated at the White King site, no downgradient uranium was detected, even though pore water samples in the protore stockpile were over 27,000 pCi/L (10^6 Bq/m^3). The overburden stockpile activities were less than 18 pCi/L (670 Bq/m^3), with a concentration of only 75 pCi/L (2775 Bq/m^3) immediately under the protore stockpile (Weston 1997). Thus, the uranium appears to be immobile, with a high K_d, at this site. Radium, in the form of radium sulfate, apparently had not migrated at all. In the 1983 EPA report to Congress, soil profiles obtained at a uranium mine in Wyoming also showed no downward migration of radionuclides (U.S. EPA 1983c).

Table 3.12. Look-up Table for Estimated Range of K_d Values for Uranium Based on pH

K_d (mL/g)	pH Levels							
	3	4	5	6	7	8	9	10
Minimum	< 1	0.4	25	100	63	0.4	< 1	< 1
Maximum	32	5,000	160,000	1,000,000	630,000	250,000	7,900	5

Source: U.S. EPA 1999

Table 3.13. Soil Screening Values for Uranium as a Function of K_d
Uranium (MCL = 30 μg/L ~ 20 pCi/L ~ 760 Bq/m^3)

Target Concentration	Assumed Partition Coefficient (K_d) (L/kg)				
	1	10	25	50	100
	Soil Screening Values (pCi/g Above Background Levels) Resulting in Groundwater Target Concentration Using the Groundwater Soil Screening Approach				
30 μg/L[8]	0.5	4	10	21	41

In contrast to the White King/Lucky Lass site, at Midnite Mine the groundwater indicator map from preliminary investigation work (U.S. EPA 2003c) plots concentration exceedances for shallow and deep wells. Uranium and other metals have been detected in several of the downgradient alluvial wells and in a couple of shallow bedrock aquifer wells adjacent to a pit and a stockpile.

The Yazzie-312 Mine has no near-surface water table because of the dry Arizona climate. There is a confined aquifer at 105 feet (32 m) below ground surface in the southern part of the site in a sand-and-gravel unit, with a static water level of 27 feet (8.2 m) below ground surface. This unit was thought to be part of a former alluvial channel, since no water was found in another well north of the mine. Since only 2.6 pCi/L (96 Bq/m^3) uranium was in the well water while 173 pCi/L (6,400 Bq/m^3) was in the pit water, the interpretation is that the pit water is not contributing to the radionuclide concentration in the aquifer. On the other hand, Longsworth

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[8] Conversion factor for naturally occurring uranium from μg/L to pCi/L (U.S. EPA 2000d): 0.67 pCi/μg

(1994) measured shallow groundwater in the vicinity of mines in the Monument Valley area of Arizona and Utah with significant levels of uranium, radium, and radon (up to 14,000 pCi/L U-238, 110 pCi/L Ra-226, and 250,000 pCi/L of Rn-222). The impact on groundwater from surface and near-surface uranium mines would appear to be highly dependent on local geological and hydrological conditions.

3.7.2 Uranium Plume Migration

In a review of uranium plumes in groundwater from natural analogues, in-situ leaching operations, and uranium mill tailings sites, Colon et al. (2001) identified a "clear and reasonably consistent picture of [uranium] plume behavior" in which plumes appear to reach a steady-state condition: the plumes rarely exceed 1.25 miles (2 km) in length and exhibit natural attenuation under different circumstances, with the low-pH in-situ leaching process contributing to the greatest plume distances. Of the natural analogues, the maximum axial[9] plume length was 1 mile (1.6 km) from the Oklo uranium deposit that acted as a natural reactor ~ 2 billion years ago. If this attenuation were to hold true at uranium mines, the distance of influence on uranium transport from an abandoned uranium mine (in the absence of added acids) in the groundwater could be less than 1.25 miles (2 km). Fracture networks, facilitated (colloid) transport, or other site-specific characteristics may act to limit this attenuation.

3.7.3 Radium

Information on radium soil-water distribution coefficients is less common, but radium K_d values that span a large range are found in the literature. U.S. EPA (2004) cautions the reader that many of the high values are suspect, because they may be the result of co-precipitation of radium with other ionic species, rather than absorption of radium itself. One EPA study indicates that very little radium is available for transport, and strong acids were necessary to extract the radium (DeLaune et al. 1996). Tachi et al. (2001) calculated K_ds of 10^2–10^4 mL/g for bentonite clays with a dependence on pH. U.S. EPA (2004) mentions one study of four sandy soils from Utah with a range of radium K_d values from 214 to 354 ml/g for pH that varies between 7.6 and 8.0. EPA (2004) confirms the paucity of K_d data, stating: "Development of K_d look-up tables for radium is not possible given the minimal number of adsorption studies." U.S. EPA (ibid.) then goes on to suggest the use of the K_d table for strontium presented by U.S. EPA (1999, Vol. 2) as general guidance for radium. This table is reproduced as Table 3.14. Table 3.15 provides SSLs for radium as a function of K_d for a range of K_ds from 1 to 500.

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[9] Along the center line of the contamination where the greatest concentration would be expected.

Table 3.14. Relationship Between pH Levels and Strontium Mobility as a Surrogate for Radium

Look-up table for estimated range of K_d values for strontium as a surrogate for radium based on clay content and pH. [Tabulated values pertain to systems consisting of natural soils (as opposed to pure mineral phases), low ionic strength (< 0.1 M), low humic material concentrations (<5 mg/l), no organic chelates (such as EDTA), and oxidizing conditions.]

K_d (ml/g)	Soil Clay Content (wt.%)								
	< 4%			4 - 20%			20 - 60%		
	pH			pH			pH		
	< 5	5 - 8	8 – 10	< 5	5 – 8	8 - 10	< 5	5 - 8	8 – 10
Minimum	1	2	3	10	15	20	100	200	300
Maximum	40	60	120	150	200	300	1,500	1,600	1,700

Table 3.15. Soil Screening Values for Radium as a Function of K_d

Radium (MCL = 5 pCi/L [185 Bq/m^3])

Target Concentration	Assumed Partition Coefficient					
	1	10	25	50	100	500
	Soil Screening Levels Concentration Values (pCi/g) Above Background Resulting in Target Groundwater Concentration					
5 pCi/L	0.12	1.0	2.5	5	10	50

3.7.4 Potential for Groundwater Infiltration and Contamination

From Figure 3.11 below, the general annual precipitation range for the Colorado Plateau area is 5-15 inches (13-38 cm). This area also has high evapotranspiration rates. The 1983 EPA Report to Congress (U.S. EPA 1983a, b, and c) estimated that about 97 percent of the precipitation was lost to evapotranspiration. Evaporation tables indicate that the general area experiences greater than 75 inches (190 cm) of evapotranspiration annually. Thus, very little precipitation infiltrates. The Maxey-Eakin empirical method for estimating recharge in the southwest (Maxey and Eakin, 1949) assumes recharge would be zero if precipitation was less than 8 inches (20.3 cm/y), and only 3% if precipitation was between 8-12 inches (20.3-30.4 cm/y). Flint et al. (2002) modified this for areas of shallow soil, so that the minimum precipitation threshold for recharge to occur was 10 cm/y.

Thus, for 15 inches/y (38.1 cm/y) of precipitation, or the maximum of the range of annual precipitation in the Colorado Plateau, the average recharge would be ~0.5 inches/y (1.1 cm/y). If this average value is assumed to be a simple velocity estimate to an aquifer and assuming no retardation, it would take hundreds of years or longer to reach an aquifer at depth. Doubling the velocity (i.e., infiltration rate) would reduce the travel time by one-half. Thus, abandoned uranium mines in the proximity of shallow aquifers may contaminate the aquifer within tens of years, but this process would take longer for the deeper mines. This simple analysis suggests that the abandoned uranium mines that don't intersect aquifers pose a greater immediate risk from surface pathways and use than from the groundwater pathway.

Site-specific characteristics such as precipitation, depth to water, soil characteristics (e.g., permeability or pH), or presence or absence of fractures, would dictate the actual infiltration, potential recharge and potential to contaminate an aquifer, and the time frame over which such contamination could occur. Once the radionuclide enters an aquifer, its transport would be dependent on several site-specific factors—including the aquifer's permeability, water velocity, and chemistry (e.g., pH)—that affect retardation. Although much of the discussion in this section has focused on radionuclides, similar concepts apply if metals are also present at a site.

Figure 3.11. Average Precipitation (inches/year) for the Western United States

The Colorado Plateau, where many of the uranium mines are or were located, is a region characterized, in general, by low precipitation and high evapotranspiration.
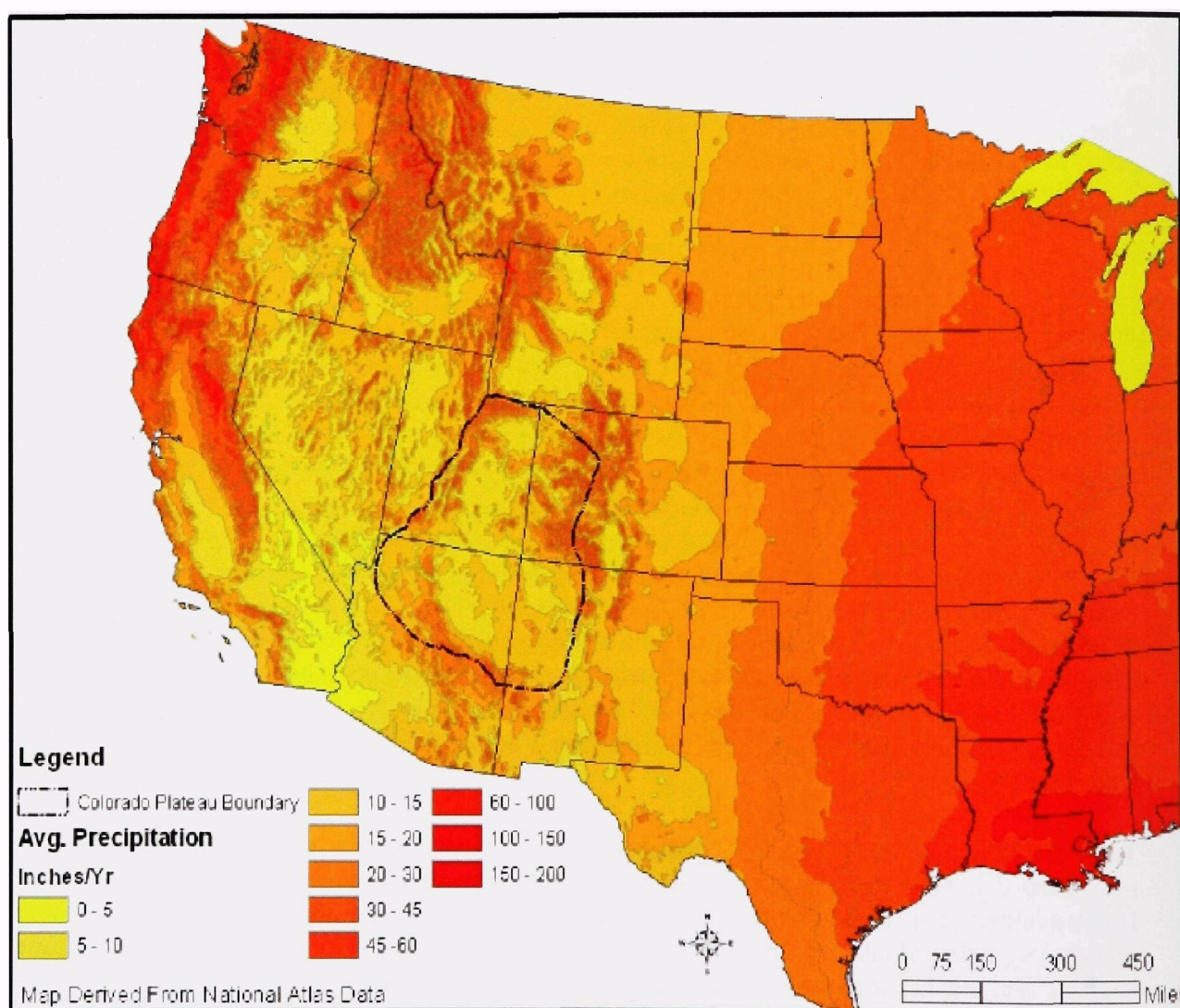
3.8   Consideration of Multiple Exposure Pathways

The fundamental criterion for applying the SSLs to a single exposure pathway is that $C_i \leq SSL_{i,k}$; that is, the concentration of pollutant i, C_i, is less than the SSL for pathway k, $SSK_{i,k}$. This implies that, for multiple exposure pathways, the SSL should be reduced to account for additive contributions to the pollutant intake from these additional pathways such that:

$$C_i/SSL_{i,1} + C_i/SSL_{i,2} + C_i/SSL_{i,3} + \ldots C_i/SSL_{i,k} \leq 1.0.$$

Dividing both sides by the concentration term C_i and inverting the equation gives:

$$C_i \leq 1/[1/SSL_{i,1} + 1/SSL_{i,2} + 1/SSL_{i,3} + \ldots 1/SSL_{i,k}].$$

The term on the right side may be viewed as a multi-pathway SSL. Tables 3.16, 3.17, and 3.18 show the application of this methodology to the external exposure, soil ingestion, and inhalation of fugitive dust pathways for the on-site exposure scenario discussed earlier in this chapter. The SSLs for external exposure and soil ingestion are listed in Tables 3.2 – 3.7. The calculation of SSLs for the inhalation of fugitive dust is discussed in the text. The risk from recreational use of off-road vehicles is not included, because the riders of these vehicles will not, in general, be the same individuals exposed in the other on-site scenarios. Likewise, the consumption of drinking water from a well would affect residents on or off the site many years in the future, after the activity has percolated into the groundwater. These would not be the same individuals exposed to the radioactivity in the surface soil due to recreational use of the site at the present time. However, for a particular site the risk from drinking surface or near-surface water could be added to risks from the other pathways. However, risk estimates conducted for this chapter indicate that the risks in the recreational scenario from external exposure are much greater than from drinking water contaminated with radionuclides.

A comparison of the multi-pathway SSLs for Ra-226 listed in Table 3.16 with the SSLs for external exposure shown in Table 3.2 shows a difference of about 1.75%; thus, the external exposure pathway for this nuclide and its progeny is dominant, and the other pathways make minor contributions to the total risk. A similar comparison for Th-232, using the SSLs in Tables 3.3 and 3.17 shows an even smaller difference—about 1.2%—indicating that the external exposure pathway is dominant for this nuclide and its progeny. This is not the case for natural uranium; although external exposure constitutes over 86% of the risk, soil ingestion makes a significant contribution. The inhalation of fugitive dust makes a minor contribution. Figures 3.12 through 3.14 portray the same data in graphical form.

Table 3.16. Multi-pathway Soil Screening Levels for Ra-226

Exposure Frequency (days/year)	Target Lifetime Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Ra-226 (pCi/g)					
1	21,116	4,223	2,112	422	211	42.2
14	1,508	302	151	30.2	15.1	3.02
30	704	141	70.4	14.1	7.04	1.41
52	406	81.2	40.6	8.12	4.06	0.812
140	151	30.2	15.1	3.02	1.51	0.302
350	60.3	12.1	6.03	1.21	0.603	0.121

Table 3.17. Multi-pathway Soil Screening Levels for Th-232

Exposure Frequency (days/year)	Target Lifetime Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Th-232 (pCi/g)					
1	14,674	2,935	1,467	293	146.7	29.3
14	1,048	210	105	21	10.5	2.10
30	489	97.8	48.9	9.78	4.89	0.978
52	282	56.4	28.2	5.64	2.82	0.564
140	105	21.0	10.5	2.10	1.05	0.210
350	41.9	8.38	4.19	0.838	0.419	0.0838

Table 3.18. Multi-pathway Soil Screening Levels for Natural Uranium

Exposure Frequency (days/year)	Target Lifetime Cancer Risk					
	5×10^{-4}	1×10^{-4}	5×10^{-5}	1×10^{-5}	5×10^{-6}	1×10^{-6}
	Concentration of Natural Uranium (pCi/g U-238)					
1	751,392	150,278	75,139	15,028	7,514	1,503
14	53,671	10,734	5,367	1,073	537	107
30	25,046	5,009	2,505	501	250	50.1
52	14,450	2,890	1,445	289	144	28.9
140	5,367	1,073	537	107	53.7	10.7
350	2,147	429	215	42.9	21.5	4.29

Figure 3.12. Multi-pathway Soil Screening Levels for Ra-226
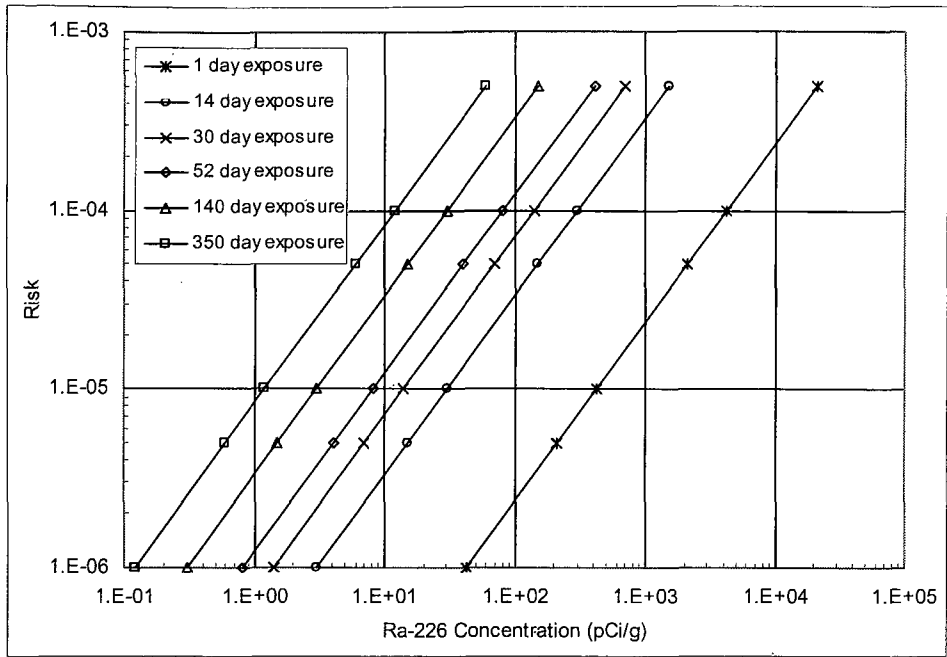

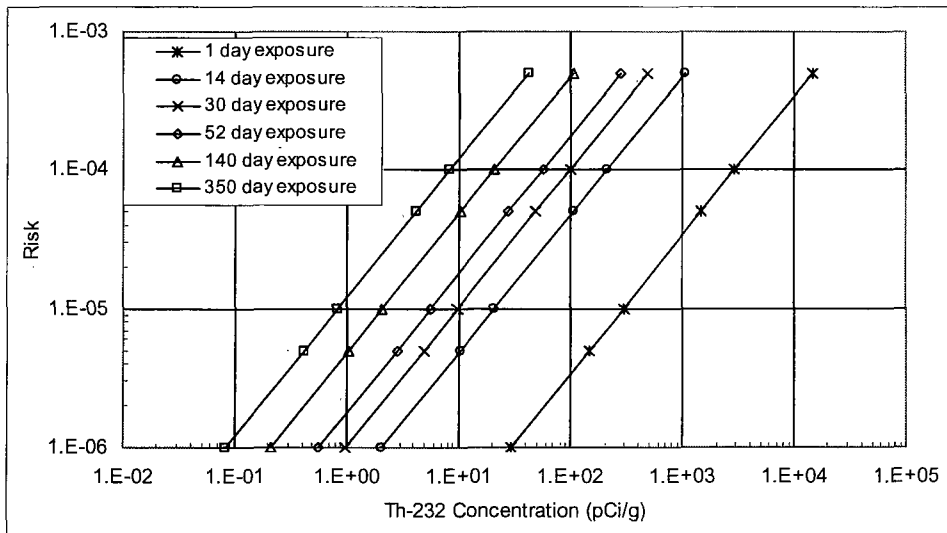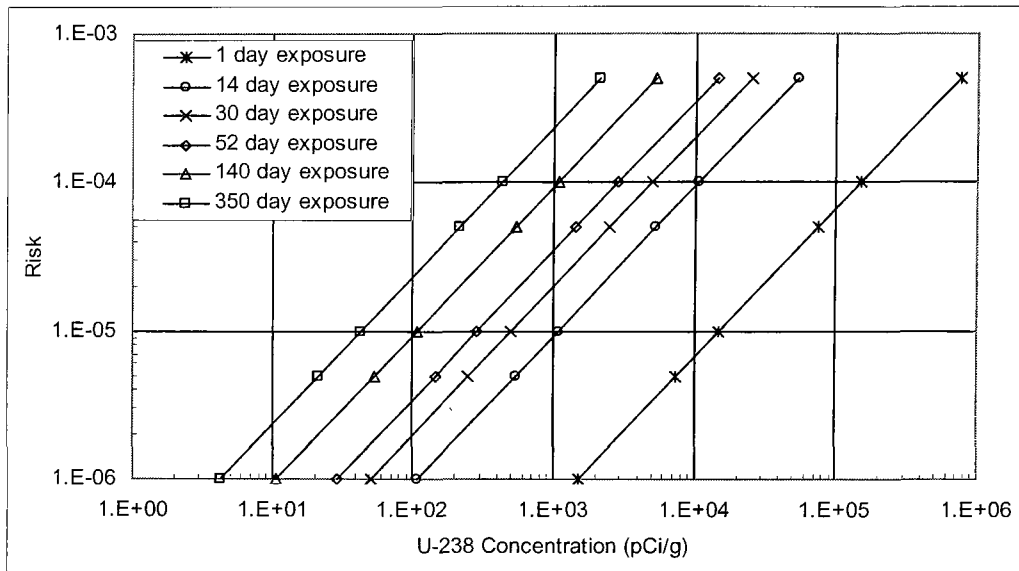## Figure 3.13. Multi-pathway Soil Screening Levels for Th-232

Figure 3.14. Multi-pathway Soil Screening Levels for U-238

4.0 RISK FROM URANIUM MINING WASTE IN BUILDING MATERIALS

In general, building materials contain low levels of radioactivity. For example, the range of natural uranium concentrations may average as low as about 0.5 ppm (0.34 pCi/g or 13 Bq/kg) total uranium activity in sandstone building materials to as high as 5 ppm (3.4 pCi/g or 130 Bq/kg) in granitic building materials. Concrete and brick buildings are estimated to contribute an average of about 10 mrem (0.1 mSv) annual effective dose equivalent (NCRP 1987) to the average person's background exposure to radiation. However, exceptions can occur to this generalization, especially in buildings constructed with materials containing uranium TENORM mine wastes. In the Grand Junction, Colorado area, thousands of homes and properties were constructed using uranium mill tailings (U.S. EPA 1983a, b, c) in the past as a source of construction sand, gravel, and clays. However, a number of homes have also been built with materials that have been attributed to "uranium ore" that are not considered to be mill tailings. In a 1972 EPA and Atomic Energy Commission (AEC) survey intended to locate building materials contaminated with mill tailings, 537 buildings were identified where uranium ore may have been the source of gamma-ray exposure anomalies (U.S. EPA 1983b):

> *We do not know to what extent the wastes from uranium mines have been removed from mining sites and used in local and nearby communities. However, while surveying in 1972 for locations with higher-than-normal gamma radiation in the Western States to locate uranium mill tailings used in local communities, EPA and AEC identified more than 500 locations where "uranium ore" was believed to be the source of the elevated gamma radiation. The specific type of ore (mill-grade, sub-ore, low-grade waste rock) was not determined as this was beyond the scope of the survey. At some locations, however, surveyors attempted to characterize the ore by using such terms as "ore spillage," "ore specimens," "low-grade crushed ore," or "mine waste dump material." Some locations were identified as sites of former ore-buying stations [U.S. EPA 1973].*

Since it is unlikely that valuable mill-grade ore would have been widely available for off-site use, we suspect that uranium mine waste (perhaps protore) may be the source of the elevated gamma radiation levels at many of the locations where large quantities of ore material are present.

About three-fourths of the 537 buildings were in Colorado and Utah, with the rest distributed among several other states. Figure 4.1 identifies the localities from the 1972 survey that had at least one building thought to have used "uranium ore" construction materials. Many of these same localities also had additional anomalies attributed to either a radioactive source or natural radioactivity. The original report that discusses the survey is unavailable, so it is not possible at this time to determine the basis used for the attribution of the cause. Of the 53 localities with at least one anomaly attributed to uranium ore, 20 are on or within approximately 25 miles (40 km) of Bureau of Indian Affairs (BIA) Reservations. Without knowing the design of the study, it is not possible to determine the statistical significance of the survey. Nevertheless, the survey does indicate the potential problem of contaminated buildings in uranium mining areas, especially on and around Tribal lands. EPA has provided support to Tribal authorities since that time to identify buildings on Tribal lands constructed with uranium mine wastes.

Contaminated buildings are among the mine waste issues that have been publicized regarding the Navajo Nation. Although not specifically addressed herein, anecdotal information is amenable to the methods and models for dose and risk estimates contained in this report. For mattresses placed directly on a contaminated slab (reported in the *Los Angeles Times* on November 19, 2006), a geometrical variation would be applied to the analysis that follows. (As an example involving other exposure pathways, for children who "dug caves in piles of mill tailings and played in the spent mines," variations in the recreational scenario of Chapter 3 would be applied.)

A specific case of the potential problem on Tribal lands is illustrated by hogans with elevated radioactivity found in the Monument Valley area of Utah. In April 2001, EPA razed and removed a building that had been used as a hogan (sacred home) by a Navajo family. As shown in the photograph in Figure 4.2, the hogan was a small, one-room round structure with a concrete slab for a floor and stucco walls, although the building originally had a dirt floor. Figure 4.3 is a picture of another house taken from the vantage point of uranium mine workings.

Figure 4-1.   Locations of Building Gamma Anomalies Due to Uranium Ore from 1973 EPA-AEC Study
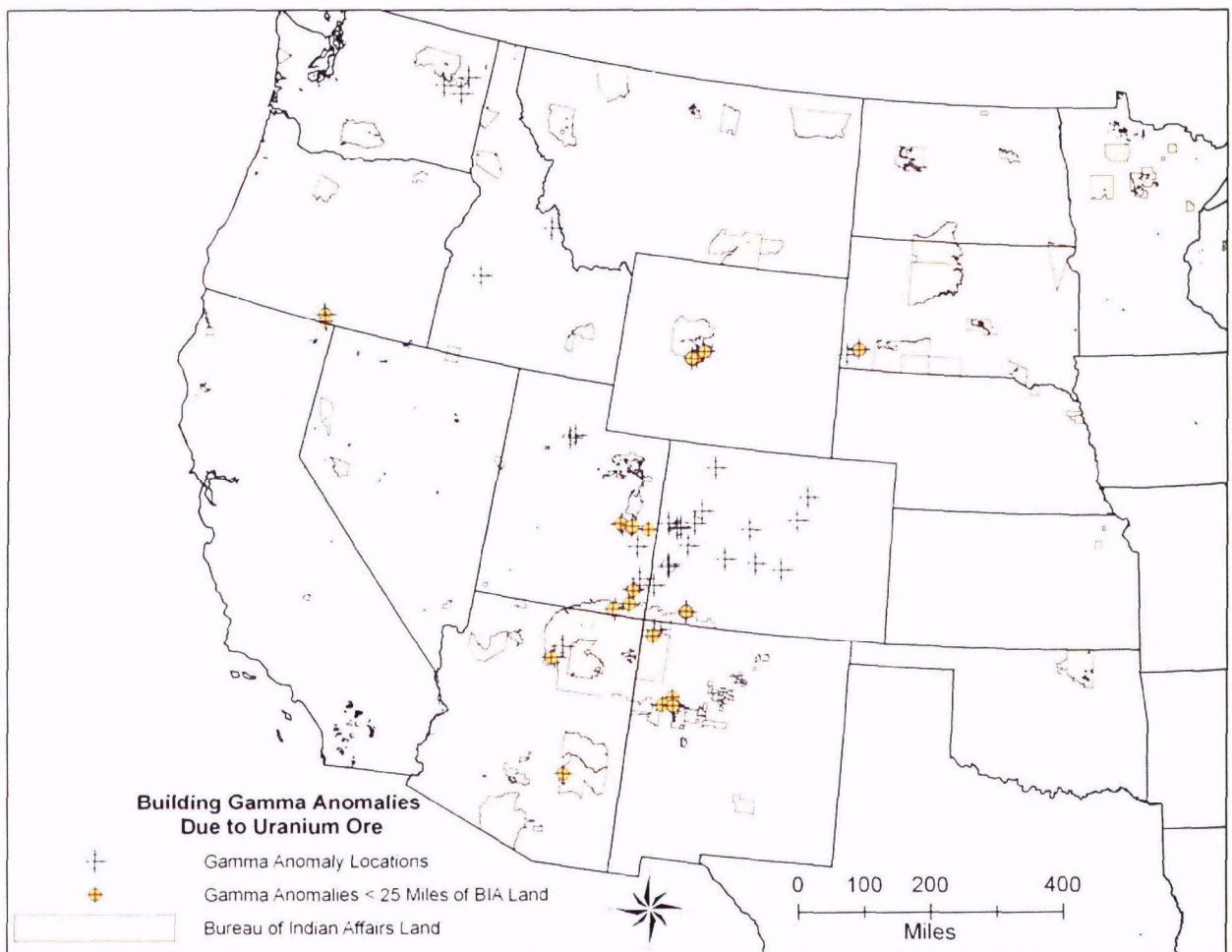
Source: U.S. EPA.

Short-term gamma-ray exposure rates and radon concentrations were measured prior to the demolition of the hogan (Sowder et al. 2001). Radiation exposures were between 370 µR/h and 600 µR/h. This is equivalent to doses in air of 325–525 µrad/h (~3–5 µGy/h). (Typical indoor background dose rates are in the range of 1.2–16 µrad/h [12–160 nGy/h]). Several stones in the hogan exhibited levels of 1,000 µR/hour on contact. Short-term indoor radon measurements using multiple methods averaged 50–90 pCi/L (1,850–3,300 Bq/m^3) under pseudo-closed conditions. Outdoor exposure rates as high as 75 µR /hour at 3.3 feet (1 m) from the structure were observed. Stones used in the exterior construction produced exposure rates of 500–1,000 µR/hour. Inspection of the floor after demolition revealed that uranium ore had been used as aggregate for the concrete. Apparently, the source of the sand and stones in the building material was a nearby uranium mine or outcrop adjacent to the mine (possibly the Skylight Mine). Other possibilities for the material include mine-waste material debris piles alongside roads, such as the one in Figure 4.4, which is on Navajo Nation land. Readily available construction materials, including clay, sand, gravel, cobbles, and boulders in above-ground piles, make them attractive for houses, stoves, chimneys, and barbecues, and for stucco, cement for log houses, driveways, walkways, and fill dirt.

Figure 4-2.   Monument Valley Navajo Hogan

Monument Valley Navajo family hogan razed due to high gamma readings. Note the talus in back, much of which originated from Skylight Mine on top of the mesa directly above.
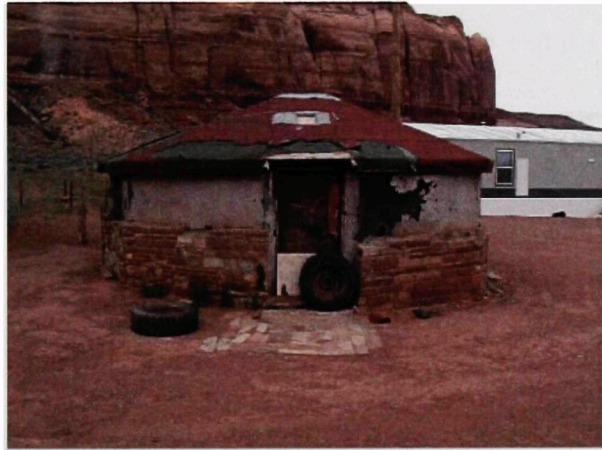
Photograph by Andrew Sowder (U.S. EPA)

Figure 4-3.   Navajo Home in Proximity to Uranium Mine

This picture is another example of the proximity of some homes to uranium mines.
A New Mexico mine, now reclaimed, lies in the foreground of the picture, while the house
in the background was originally constructed with mine waste but has since be
reconstructed to remove the contaminated material.

Photograph by Loren Setlow (U.S. EPA)

Figure 4-4.   Uranium Mine Debris Pile

Debris pile of uranium mine wastes just off a road on Navajo Nation land.
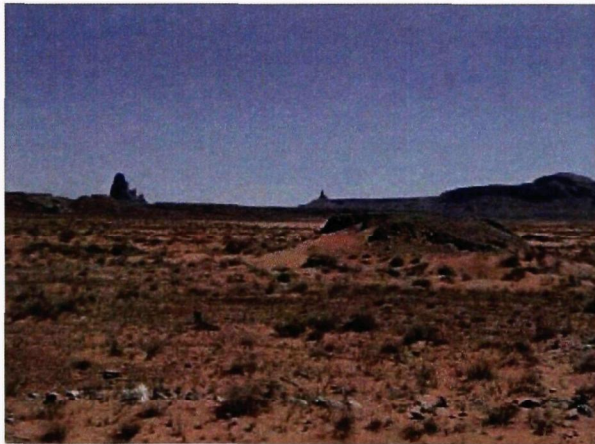
Photograph by Andrew Sowder, (U.S. EPA)

4.1   Building Materials Analysis

Given that some homes incorporate uranium mine waste building material, the question arises as to the radium and uranium concentrations in these materials that would result in exposure levels of concern. To identify potential gamma and radon exposures over a range of uranium and

radium concentrations from contaminated concrete used as building materials for the floor and each wall, we used the RESRAD-BUILD 3.21 computer code (Yu et al. 2001).

The building we used for our modeling was based on the concrete Monument Valley Navajo hogan. The building modeled had one room with a floor area of 16.4 × 16.4 feet or 269 ft^2 (5 × 5 m or 25 m^2). Each wall is assumed to be 8.2 feet (2.5 m) high, 16.4 feet (5 m) long, with an area of 134 ft^2 (12.5 m^2) (Figure 4.5). Occupancy is assumed to be 70 percent for 365 days a year (NAS 1999). Since the calculations were scoping in nature, we used the RESRAD-BUILD default parameters. We assumed that the floors and walls were made of concrete, the radium and uranium concentrations were equal, and the receptor was at a height of 3.28 feet (1 m). However, RESRAD-BUILD calculates the contribution of the floor and the wall, so that the contribution from each part can be separated. The calculations assume no contribution from the soil beneath the concrete floor. The concrete was assumed to be 6 inches (15 cm) thick, with a density of 2.4 g/cm^3. Results are presented in doses, which are calculated by RESRAD-BUILD.

4.1.1   Results of Building Materials Analysis

From the modeling conducted using RESRAD-BUILD, we calculated doses from external exposures to U-238 and Ra-226 in full secular equilibrium with their short-lived progenies.[1] These doses are listed in Tables 4.1 and 4.2 and are presented graphically in Figures 4.6 and 4.7.

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[1] This is somewhat different from the way uranium was characterized in the analyses presented in Chapter 3. In the latter case, all uranium isotopes were assumed to be present in proportion to their natural abundance, and all long-lived progenies except Ra-226 and its decay chain were included, whereas the analysis in this chapter addresses only U-238, the dominant isotope, and its short-lived progeny.

Figure 4-5.   Navajo Hogan Building Model

This 3-D schematic of the Navajo hogan indicates the sources of exposure modeled, with the floor as source 1, and the walls as sources 2 - 5. The origin of the geometry is at the lower left-hand corner, where z represents the vertical extent of the room and x and y represent the lateral extent of the walls.
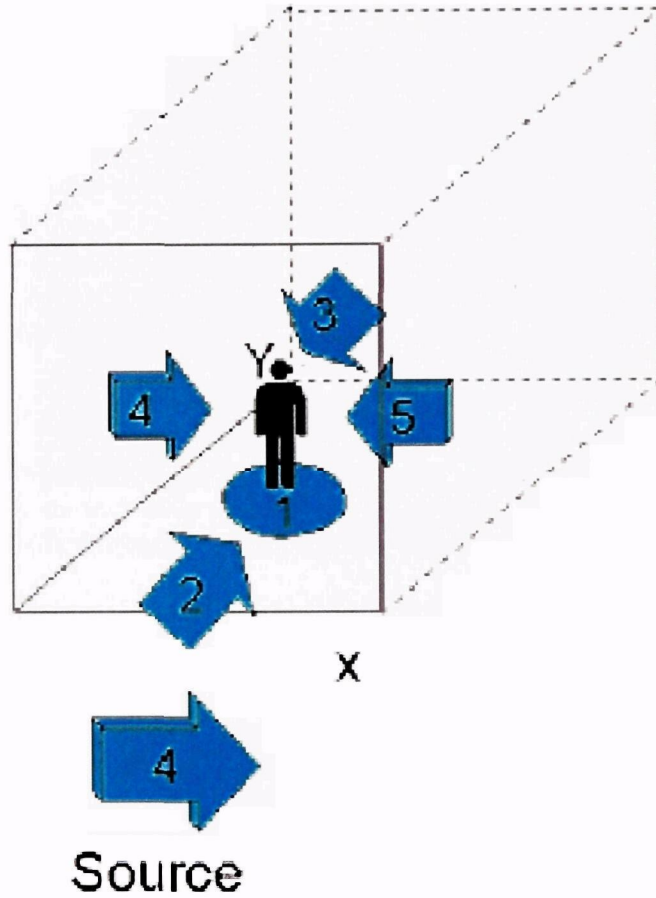
Table 4-1.   Doses from 30 Years of External Exposure to U-238 in a Navajo Hogan

The dose from the floor is about equal to all of the walls combined.

Activity Concentration (pCi/g) (Bq/kg)	Dose from Floor (mrem) (mSv)	Dose from One Wall (mrem) (mSv)
1 (37)	1.88 (.02)	0.554 (.006)
50 (1850)	93.9 (.9)	27.7 (.3)
150 (5550)	282 (2.8)	83.1 (.8)

Figure 4-6. Doses from 30 Years of External Exposure to U-238 in a Navajo Hogan

The floor in the Navajo hogan contributed the most gamma exposure.
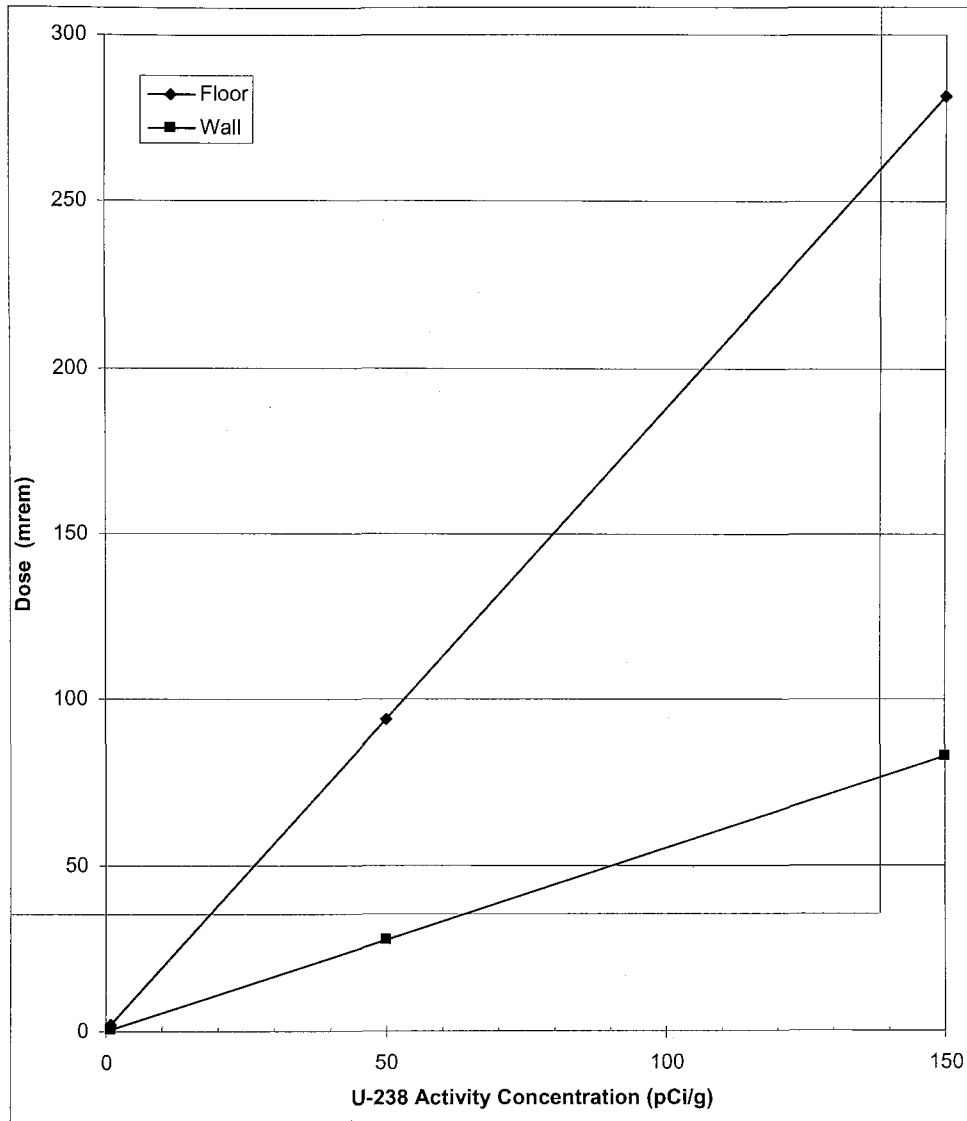
Doses are listed from external exposure to the floor and to a single wall to allow for an estimate of the dose if just a concrete slab is contaminated. The calculated dose from a single wall is between one-fourth and one-third the calculated dose from the floor. The total dose from the entire structure may be estimated by multiplying the dose from one wall by a factor of four and adding the result to the dose from the floor.

In order that the uranium in building materials could pose a significant risk from external exposure, the uranium concentrations in the building materials must be quite high relative to background concentrations. For example, for a dose of 300 mrem (3 mSv) from the uranium in the floor over a 30-year period, the U-238 activity would need to be about 180 pCi/g

(6,660 Bq/kg or about 540 ppm). However, this level could be found in uranium overburden, and especially in protore.

Table 4-2. **Doses from 30 years of External Exposure to Ra-226 in a Navajo Hogan**

The dose from the floor is about equal to all of the walls combined.

Activity Concentration (pCi/g) (Bq/Kg)	Dose from Floor (mrem)(mSv)	Dose from One Wall (mrem)(mSv)
1 (37)	139 (1.4)	40 (.4)
10 (370)	1394 (14)	401 (4)
20 (740)	2787 (28)	801 (8)

Figure 4-7. **Doses from 30 years of External Exposure to Ra-226 in a Navajo Hogan**
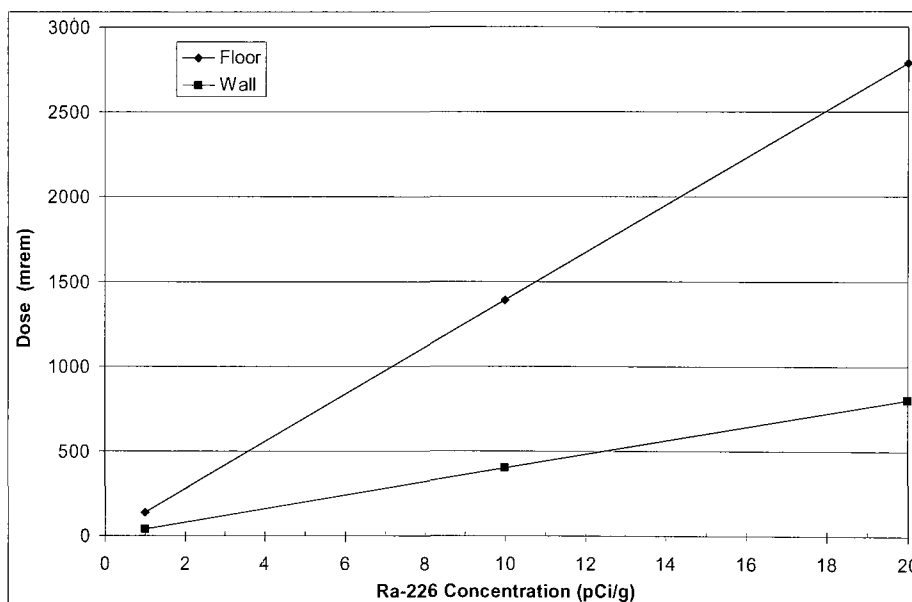
Although U-238 would contribute to the overall radiation exposure, the Ra-226 in the mining waste materials is the more hazardous of the two radionuclides. A concentration of 1 pCi/g (37 Bq/kg) of Ra-226 in the floor is estimated to result in a dose of about 140 mrem (1.4 mSv) during 30 years of external exposure. According to the 1985 EPA report to Congress, most of the uranium mines sampled had Ra-226 concentrations of 20 pCi/g (740 Bq/kg) or more in the waste. If waste with this radium activity were incorporated into a concrete floor slab, it would result in a 30-year dose of about 2.8 rem (28 mSv). Figure 4.7 illustrates the relationship between Ra-226 concentrations and doses from external exposure calculated with RESRAD-BUILD.

The dose rate from the floor and four walls is approximately 50 μrem/h per pCi/g of Ra-226 (1.4×10^{-4} mSv/hr per Bq/kg). If the exposure rates measured in the Monument Valley Navajo hogan above were primarily from radium in the floor and walls, and the measurements were

made in the center of the hogan, we estimate that the materials in the hogan contained up to about 10 pCi/g of Ra-226 (370 Bq/kg).

In addition to direct radiation exposure, radon generation from radioactive decay could also contribute to risk posed by living in buildings constructed with uranium mine waste, depending on frequency of air exchange and other factors. As mentioned above in the Sowder et al. (2001) study of the hogan in Monument Valley, Utah, short-term indoor radon measurements using multiple methods averaged 50–90 pCi/L (1,850–3,300 Bq/m3) under pseudo-closed conditions. This greatly exceeds EPA's radon action level of 4 pCi/L (U.S. EPA 2004). However, studies of other houses constructed with uranium mine waste on Navajo Lands found many had much lower concentrations of radon, which may have been the result of construction methods and chimneys which allowed inside air to quickly exit the buildings (L. Setlow, U.S.EPA, personal communication, 2007)

4.2 Risk of Exposure of On-site Residents to Uranium Mining Waste

As described in Volume 1, the overburden and protore are typically left as piles, and consist of poorly sorted materials ranging from clay-sized fractions to boulders. Thus, it is not likely that the material would have a building located on it unless it has been flattened by erosion, was accessible from a higher elevation, or had been disposed off a hillside to create a terrace. In populated areas, however, it could be possible for the material to be spread out and a home subsequently built upon the leveled material. This scenario is included here as an upper bound on the potential risks from uranium mines, but it is not a focus of this scoping analysis because there are already guidelines for the amount of radium that is acceptable for Superfund remediation actions (U.S. EPA 1997a) and in the standards at 40 CFR 192 promulgated by EPA under the Uranium Mill Tailings Radiation Control Act (UMTRCA).[2]

The results of a study in Florida (U.S. EPA 1979) developed a relationship between Ra-226 in soil and indoor working levels (WL). The 1983 EPA report to Congress (U.S. EPA 1983b) references this document and assumed a similar relationship for a home built on uranium mine waste material. These data indicate that a concentration of 1 pCi/g (37 Bq/Kg) of Ra-226 in soil produces an indoor concentration of 1 pCi/L (0.03 Bq/L) of Rn-222, which is equal to 0.004 WL, assuming an equilibrium factor of 0.4 (UNSCEAR 2000). Thus, a concentration of 5 pCi/g (185 Bq/kg) of Ra-226 in the soil would produce an indoor radon concentration that is above the current recommended action level of 4 pCi/L (148 Bq/m^3).

The lifetime risk from the indoor radon decay products using current risk estimates is included in Table 4.3, along with the original estimate from 1983. Since the 1983 report was published, numerous studies have concluded that indoor radon concentrations are influenced by a

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[2] EPA regulations at 40 CFR 192 include limitations for radium and radon at UMTRCA sites: The disposal areas must be designed to limit releases of radon-222 from uranium byproduct materials to the atmosphere so as not to exceed an average release rate of 20 pCi/m^2/s. This requirement, however, applies only to a portion of a disposal site that contains a concentration of radium-226 that, as a result of uranium byproduct material, exceeds the background level by more than 5 pCi/g (185 Bq/Kg) averaged over the first 15 cm below the surface, or more than 15 pCi/g (555 Bq/Kg), averaged over 15 cm thick layers more than 15 cm below the surface.

combination of factors, including foundation slab integrity and permeability, indoor and soil pressure differentials, and the soil radium concentration. Thus, it is difficult to predict the indoor radon concentration based on soil parameters. However, modeling can provide a general indication of the radium/radon relationship.

Table 4-3.   Estimated Lifetime Risk of Fatal Lung Cancer from Living on Contaminated Land

This table assumes an average individual is inside the home 75 percent of the time for the 1983 estimate, and 70 percent occupancy for the 2006 estimate. Because the estimate of risk per working level has increased from that used in 1983, and it is greater than the decrease in occupancy, the estimated cancer risk is higher in 2006.

Rasium-226 in Soil (pCi/g) (Bq/Kg)	Indoor Working Levels (WL)	Lifetime Risk of Fatal Lung Cancer	
		1983	2006*
5 (185)	0.02	0.025	0.029
10 (370)	0.04	0.050	0.059
20 (740)	0.08	0.100	0.117
30 (1110)	0.12	0.150	0.176

*   The 2006 risk estimate is calculated using the equation presented in Chapter 1 of this volume, under the Applicability of 1983 Risk Estimates section.
Source: U.S. EPA 1983b.

Additional modeling was conducted using the RESRAD computer code, which embodies a one-dimensional multi-pathway model for residual radioactivity at sites (Yu et al. 2001). This code was chosen because of its applicability, widespread use, testing and review, and ease of use. Most of the RESRAD default values were chosen for this scoping analysis. For the Colorado Plateau on-site resident scenario, we initially assumed that consumption of groundwater was not an exposure pathway. We assumed a ventilation rate of 0.5/h, that the foundation was at the surface with no basement, and that 70 percent of the time was spent indoors and 30 percent outdoors. With these assumptions, the model predicted indoor radon and external exposure to direct penetrating radiation to be the major source of radiation exposure, with the indoor radon exposure higher than the external exposure. Most of the risk from living on contaminated materials is from the decay of indoor radon. When the ventilation rate is reduced to 0.25/h, the working levels increase (~0.031 WL for 5 pCi/g (185 Bq/Kg) radium). When we repeated the analysis with the drinking-water pathway included, using a value of ~82 feet (25 meters) for depth to the aquifer and conservative parameters, such as an evaporation coefficient of 0.5, and K_ds of 10 mL/g for uranium and radium, the indoor radon and external exposure pathways are still dominant. Pending any consideration of the food chain, which is of most potential importance for subsistence ranching and hunting, the risks from uranium are dwarfed by the risks posed by radium and radon.

Uranium mine wastes have the potential to create very high risks to an on-site resident, as indicated by this analysis and the analysis of the White King/Lucky Lass mine site. Ra-226 is the primary contributor to risk from the external exposure and indoor radon inhalation pathways. While the indoor radon concentrations and corresponding working levels resulting from a given concentration of Ra-226 depend on multiple factors, it is possible to estimate approximate relationships among these quantities.

5.0 POTENTIAL ECOLOGICAL IMPACTS FROM URANIUM MINES

This document has focused on the potential risks to humans from exposures to unreclaimed uranium mining materials. The potential effects on relevant ecosystems have not been addressed, because they are beyond the scope of this report. Although not analyzed here, ecosystem effects are briefly mentioned because of the potential importance of the topic in the consideration of unreclaimed uranium mines. Although the Superfund characterization process includes radionuclides in the ecological risk assessment and for some individual species, the lack of an accepted standard methodology for demonstrating protection of ecosystems from radiation makes the identification of potential effects due to uranium mining difficult. There is, however, a general framework for ecological risk assessment. As defined in the 1992 Framework for Ecological Risk Assessment (U.S. EPA 1992), an ecological risk assessment (ERA) is a process for evaluating the likelihood that adverse ecological effects may occur, or are occurring, as a result of exposure to one or more stressors.[1] This framework was applied in the Superfund guidance, *Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessments*, Interim Final (U.S. EPA 1997b).

Ecological risk assessment addresses two major elements, characterization of effects and characterization of exposure, which provide the focus for three primary phases of activities: problem formulation, analysis, and risk characterization (U.S. EPA 1998). In these three phases, the risk assessment process provides a way to develop, organize and present scientific information so that it is relevant to environmental decisions. Issues to consider are spatial and temporal, along with assessment endpoints, and whether it is the terrestrial or aquatic environments that are of concern (U.S. EPA 2000a). When conducted for a particular area such as a watershed, the ecological risk assessment process can be used to identify vulnerable and valued resources, prioritize data collection activity, and link human activities with their potential effects. However, a risk does not exist unless: (1) the stressor has the ability to cause one or more adverse effects, and (2) it co-occurs with or contacts an ecological component long enough and at a sufficient intensity to elicit the identified adverse effect (U.S. EPA 1997b). As discussed in this chapter, it is very possible that the stressors to the surrounding ecosystem may not be the radioactive materials, but rather the other hazardous constituents that may be associated with uranium mine sites.

Efforts are underway to extend the ecological risk assessment approach to radiation. In recent work, Jones et al. (2003) state that, "potentially susceptible receptors [to radiation] include vertebrates and terrestrial plants." EPA has no radiation dose standards for the protection of flora and fauna, but the Department of Energy (DOE) (Jones et al. 2003) has suggested levels of exposure for the protection for the following: natural populations of aquatic biota (1 rad d-1 or 10 mGy d-1), terrestrial plants (1 rad d-1 or 10 mGy d-1) and animals (0.1 rad d-1 or 1 mGy d-1).[2] The question remains whether these levels are indeed protective.

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[1] A "stressor" is any chemical, physical, or biological entity that can induce adverse effects on individuals, populations, communities, or ecosystems.

[2] 1 gray = 100 rad; thus 1 mGy = 0.001 Gy = 0.1 rad or 100 mrad.

DOE has recently issued a technical standard on applying these levels in the document *A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota* (U.S. DOE 2002). The graded screening approach uses three tiers, becoming progressively more rigorous and detailed: a scoping assessment, a screening ERA, and a more detailed ERA that uses site-specific information (Jones et al. 2003). As the tiers become more site-specific, the assumptions become less conservative. In the screening phase, this process uses biota concentration guides (BCGs) for water and sediment for evaluating aquatic systems, and water and soil for evaluating a terrestrial system. These BCGs are set "so that doses received by real biota exposed to such concentrations are not expected ever to exceed the biota dose limits" (Higley et al. 2003). The BCGs for aquatic and terrestrial systems are reproduced in Tables 5.1 and 5.2. The radiation levels found at some of the uranium mines where sub-ore and ore-grade materials have been left on site could exceed the levels identified by DOE, especially for radium.

Table 5-1.   Biota Concentration Guides (BCGs) for Water and Sediment for Evaluation of an Aquatic System

Nuclide	BCG for Water		Organism Responsible for Limiting Dose in Water	BCG for Sediment		Organism Responsible for Limiting Dose in Water
	Bq/m^3	pCi/L		Bq/kg	pCi/g	
^{226}Ra	2×10^2	5.4×10^0	Riparian[a] Animal	4×10^3	1.1×10^2	Riparian Animal
^{228}Ra	2×10^2	5.4×10^0	Riparian Animal	3×10^3	8.1×10^1	Riparian Animal
^{232}Th	1×10^4	2.7×10^2	Aquatic Animal	5×10^4	1.4×10^3	Riparian Animal
^{233}U	7×10^3	1.9×10^2	Aquatic Animal	2×10^5	5.4×10^3	Riparian Animal
^{234}U	7×10^3	1.9×10^2	Aquatic Animal	2×10^5	5.4×10^3	Riparian Animal
^{235}U	8×10^3	2.2×10^2	Aquatic Animal	1×10^5	2.7×10^3	Riparian Animal
^{238}U	8×10^3	2.2×10^2	Aquatic Animal	9×10^4	2.4×10^3	Riparian Animal

a   A "Riparian Animal" is an animal that lives on a riverbank and hence spends time on land and in water, e.g., a muskrat.
Source: Reproduced from Higley et al. 2003.

Table 5-2.   Biota Concentration Guides for Water and Soil for Evaluation of a Terrestrial System

Nuclide	BCG for Water		Organism Responsible for Limiting Dose in Water	BCG for Sediment		Organism Responsible for Limiting Dose in Water
	Bq/m^3	pCi/L		Bq/kg	Bq/m^3	
^{226}Ra	3×10^5	8.1×10^3	Terrestrial Animal	2×10^3	5.4×10^1	Terrestrial Animal
^{228}Ra	3×10^5	8.1×10^3	Terrestrial Animal	2×10^3	5.4×10^1	Terrestrial Animal
^{232}Th	2×10^6	5.4×10^4	Terrestrial Animal	6×10^4	1.6×10^3	Terrestrial Animal
^{233}U	1×10^7	2.7×10^5	Terrestrial Animal	2×10^5	5.4×10^3	Terrestrial Animal
^{234}U	1×10^7	2.7×10^5	Terrestrial Animal	2×10^5	5.4×10^3	Terrestrial Animal
^{235}U	2×10^7	5.4×10^5	Terrestrial Animal	1×10^5	2.7×10^3	Terrestrial Animal
^{238}U	2×10^7	5.4×10^5	Terrestrial Animal	6×10^4	1.6×10^3	Terrestrial Animal

Note: 1 pCi/L = 37 Bq/m3, 1 pCi/g = 37 Bq/kg
Source: Reproduced from Higley et al. 2003.

5.1   Other Metals

There could be multiple stressors from uranium mining, especially in watersheds where a high density of uranium mines could have a larger effect than a single mine. The metals associated with uranium may cause adverse ecological effects, depending on the concentration and bioavailability. Arsenic, a human carcinogen, is one and it was discussed in Chapter 3. Other common associations include copper, phosphate, molybdenum, and vanadium. Lead and selenium are additional metals noted in some Arizona mines in the EPA Abandoned Mine Lands portion of the CERCLIS3 database. See Table 5.3 for mineral ores with which uranium (and radium) may be associated. Vanadium and uranium are commonly mined together on the Colorado Plateau (U.S. EPA 2006a).

Most of the mines located in the sedimentary sandstone deposits of the southwestern United States are not in pyritic formations, and the resulting runoff waters or pit lakes are generally neutral to alkaline in character (pH of 7 or higher). Low precipitation rates and the resultant lack of water may further reduce the potential for generation of acid mine or rock drainage (AMD or ARD) from waste rock, for example, in both the Colorado Plateau and the Shirley Basin of Wyoming (U.S. EPA 2006a). For mines elsewhere, AMD/ARD can be a problem. Midnite Mine in Washington State is an example of a large uranium mine in which AMD did occur. While AMD/ARD can enhance contaminant mobility by promoting leaching from exposed wastes and mine structures, releases can also occur under neutral pH conditions (U.S. EPA 2000a).

The effects of the metals can be assessed within the Superfund methodology. An example of this was mentioned as part of the discussion of the White King/Lucky Lass Superfund site. In that ecological risk assessment, no adverse ecological effects were seen from the radioactive materials, but the associated metals did pose a potential ecological threat to a local shrew species. Other mining sites have created environmental problems, and some are on the National Priorities List for cleanup. Midnite Mine, for example, underwent a preliminary ecological risk assessment (URS 2003), and a number of metals were examined, including copper, lead, arsenic, selenium, uranium, vanadium, zinc, molybdenum, and chromium. Uranium-235, uranium-238 and thorium-232 were also evaluated. According to the final ecological risk assessment, there were situations where both the radioactivity and the metals exceeded guidelines (Lockheed Martin 2005). The record of decision concludes that, "Contaminants in surface water, ground water, surface materials, and air represent a threat to human and ecological receptors" (U.S. EPA 2006c).

Although not analyzed here, there may be environmental effects, in addition to potential human health effects, from unreclaimed uranium mines. While many of the mines are remote and may not be visited by humans, the flora and fauna would be exposed for much longer periods of time, and thus could be affected by unreclaimed mines. Issues to be considered for an ecological risk

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[3] The Comprehensive Environmental Response, Compensation and Liability Information System (CERCLIS) Database contains general information on sites across the nation and U.S. territories including location, contaminants, and cleanup actions taken. The database can be downloaded from the web at http://www.epa.gov/superfund/programs/aml/amlsite/nonnpl.htm.

assessment of unreclaimed mines could include the identification of stressors for the different types of uranium mines, affected species at different sites, the potential exposures, and the endpoints for determining effects.

Although radiological and chemical toxicity should be treated as concerns, the closure of mine shafts that have long remained unreclaimed must also be considered carefully. In parts of the country where open mine shafts have long been part of the landscape, animal species—most notably bats—may rely on those mines shafts as critical habitat. Endangered bat species have been documented nesting in unreclaimed mines. If a survey by a biologist determines the presence of bat species in an abandoned mine, adequate closure may be accomplished by means of a "bat gate," a metal grate that prevents humans from entering but allows the free passage of bats (Burghardt 2003).

Table 5-3.   Mineral Commodities with Uranium Associations

Several mineral ores often, though not always, have TENORM-associated wastes resulting from co-occurrence of uranium and radium.

Aluminum (bauxite)
Coal (and coal ash)
Copper
Fluorospar (fluorite)
Gypsum
Molybdenum
Niobium
Phosphate (phosphorus)
Potassium (potash)
Precious metals (gold, silver)
Rare earths: yttrium, lanthanum, monazite, bastanite, etc.
Tin
Titanium (leucoxene, ilmenite, rutile)
Tungsten
Vanadium
Zircon

Source: U.S. EPA 2003d.

6.0 UNCERTAINTIES

The major uncertainty in this analysis is the actual exposure that people will experience. Because many abandoned uranium mines are on federal lands, the most likely exposure scenario is recreational use, but the true nature and extent of the recreational use is unknown. Exceptions to this are Native Americans who live around the uranium mines and personnel who may work around the sites. In addition, the number of people exposed would depend on the number of mines that have been reclaimed. Some mines have been reclaimed, but the total number is unknown. In the 1983 EPA study (U.S. EPA 1983b), the authors noted that many of the mines from the 1950s and 1960s had not been reclaimed at that time. Survey work done by Otten for EPA (1998) found that in many uranium-producing states, perhaps half of the mines or more had been reclaimed. No other survey has been conducted since that time. In the 1970s, surveys identified hundreds of potential buildings constructed from what was believed to have been uranium mining-related material. However, little is known about the extent of building contamination or the level of contamination in the building materials, or whether they remain or are occupied.

Another uncertainty is the true effect uranium mines have on the ground water and the subsequent use of the water. In many parts of the Southwest, where many of the mines are located, the primary sources of drinking water are deep-lying aquifers, so shallow open-pit or underground mines may not contaminate the water because of the limited infiltration. Furthermore, since uranium mines are in mineralized areas, it can be difficult to differentiate between a groundwater problem caused by a uranium mine and naturally occurring uranium. In other instances, in areas with surface water flow, such as the Ross-Adams Mine in Alaska, or Orphan Mine in Arizona (see U.S. EPA 2006a), a local source of drinking water may be contaminated by water flowing through uranium mine waste or the mine itself, and serve as a possible ingestion pathway for radiation exposure.

The other major uncertainty involves the concentrations of contaminants. The primary radiological contaminant of concern is Ra-226, which would contribute the greatest risk—from external exposure—to the occasional recreationalist. Uranium may also be a contaminant of concern, especially if it can migrate to a drinking-water source where its chemical toxicity becomes the health hazard. There is information that can be used to bound the potential exposures to both of these radionuclides, but the concentrations vary within a site and between the true overburden and amount of protore at a specific mining location. Arsenic, a carcinogen, has been shown to be associated with uranium mine wastes and can reach high levels at mine sites, but arsenic concentrations can be highly variable. At some sites, the risk from arsenic may dominate the radiological risk, and other metals may also contribute some uncertain level of hazard. Since this analysis was done on a generic, scoping basis, site-specific analyses would remove much of the uncertainties encountered here.

7.0 CONCLUSIONS

7.1 Summary

The majority of uranium production in the U.S. has come from several hundred underground and open-pit mines out of the thousands of mines and exploration workings known to exist. Some of these have been closed and remediated, at least two have been placed on the National Priorities List (Superfund) for cleanup, and others have been in standby mode where the owners have been waiting for the price of uranium to increase, as it has in 2006. The focus of this scoping report, however, has been on an investigation of potential risks from the thousands of relatively small mines and exploration sites that were abandoned over the years. With this report we have tried to identify the most likely exposure scenario for the abandoned mines, develop a first order estimate of cancer risks using some conservative assumptions, and identify if there are potential ecological effects that may develop around these mines.

Of the thousands of uranium mines in the continental United States, most are concentrated in Colorado, Utah, Wyoming, and New Mexico, and to a lesser extent, Arizona and Texas. For the small number of uranium mines in other regions, uranium is typically a byproduct of other mineral production. Many of the Four Corners States' mines are concentrated in a small number of watersheds. Though some Superfund removal actions have taken place within the Colorado Plateau, the two uranium mines on the National Priorities List are outside of the major uranium-producing states.

Most abandoned uranium mines are likely to have elevated radium and uranium concentrations, and possibly elevated levels of other contaminants such as arsenic. An analysis of the location of uranium mine records indicates that many are on federal lands, so a primary exposure scenario pertains to short-term recreational activities, including short-term occupation. Another scenario of concern is the use of mine waste material as building materials for those situations where the mines are not remote and material can be transported by nearby populations. In the recreation scenario, short-term exposure to radium, uranium, and arsenic appears to create only minimal additional cancer risk. This additional risk is dominated by external gamma exposure associated with radium in the waste material. The radioactivity in sub-ore grade uranium mine waste can be very high, so longer-term exposures from repeated visits to a high radium/high gamma site could begin to create a higher risk, even to a recreational user. The highest end of the risk spectrum is the scenario in which abandoned mine areas are used as home sites, which could pose a significant cancer risk to any long-term inhabitant. Long-term inhabitants who live near the mine sites might also use uranium mine waste material in building materials, and they would face additional risk from those radioactive building materials. It appears that those living on western Tribal lands appear to be most at risk as potential residents on or near abandoned uranium mine sites, or from the frequent visiting or passing through contaminated sites and wastes.

In general, the risks from these sites are primarily from occasional exposures and are likely to be minimal, even with conservative assumptions. The risk resulting from frequent use of a site, however, approaches a resident's exposure. Due to the predominant recreation scenario, the risk analysis examined risks in terms of days of exposure instead of the typical annual exposure,

although 350-day scenarios have been included to represent the exposure level for one year. From the estimates of the risk provided in this document, it is possible to quickly determine a first order estimate of the risks from a site, given the predominant contaminants, with the caveat that specific site conditions and site use would need to be factored in for a more realistic risk estimate.

Many of the abandoned uranium mines occur in areas with low precipitation and deep groundwater so that risk to ground-water drinking water sources is often low for at least the short-term (tens of years). However, some abandoned uranium mines occur in areas with higher precipitation. Abandoned uranium mines that are the most likely to affect groundwater are those that intersect groundwater (e.g., underground mines or deep surface mines) or are above shallow aquifers. Both radium and uranium have had MCLs established for them in drinking water supplies, but uranium is the most likely candidate to contaminate groundwater, since radium-226 is typically more immobile. In the case of uranium, the MCL is based on the limiting effect of chemical toxicity, not the radiological properties.

Ecological effects were not a focus of this report, but they were considered. Radionuclide and other heavy metal concentrations could be high enough to affect flora and fauna around abandoned mines, especially in watersheds with a high mine density. Indeed, it may be the flora and fauna that are affected much more than human health, and it may be the non-radioactive metals that produce the more significant ecological effects. This may be especially true where uranium is a secondary commodity, such as in the Lefthand Creek watershed in Colorado. At the same time, however, species may have grown accustomed to the presence of mine shafts that remain unreclaimed, and may, in fact, rely on them for habitat.

7.2   Potential Considerations for Site Prioritization

Ideally, all abandoned uranium mine sites would be remediated; however, given budget restraints, it is recognized that the most likely sites to be remediated are those that pose the greatest threat to human health and the environment. There are a number of items that could be considered when trying to prioritize the mines to be remediated. For example, in the cases where the radionuclides are likely to reach the groundwater, surface water, or springs, uranium may be the limiting radionuclide, because it is typically more mobile than radium. Radium may most often be the limiting factor in other cases because of the risk from external exposure. Less information is known about thorium values and the importance of thorium relative to radium. In some cases, the non-radiological metals may be the most hazardous of the mine waste constituents.

7.2.1   Depth to Groundwater and Annual Precipitation

EPA considers groundwater a resource for which it is easier to prevent pollution than to treat pollution after the fact. Those uranium mines that are located in areas with shallow (<50-60 feet or <~20 meters) groundwater resources have the potential to contaminate underlying aquifers within decades. Coupled with moderate amounts of precipitation (>~20 inches or >~50 cm), radioactive and metal contaminants at uranium mines could create a groundwater problem if not addressed. Large mines and underground mines that intersect aquifers have caused groundwater contamination. A scoping study such as this can identify some potential issues in this area, but it

cannot account for all the variations in site characteristics, so the geology and hydrology of a particular site would have to be examined (e.g., pH) when making remediation decisions.

7.2.2 Frequency of Use

The main tenets of protection from radioactive materials are time, distance and shielding. At one end of the spectrum, if one were to live on the mine waste materials or be exposed to mine wastes as part of construction materials, the risk of cancer from doing so could be relatively high. The scoping analysis in this report indicates that people who spend only small amounts of time at these abandoned mines probably have low risk. This low-risk consequence changes if one of these sites gets frequent use, creating a continuum of risk which we have tried to illustrate through the use of exposure calculations based on days per year of exposure.

In addition to current uses (e.g., recreation), the potential for future population growth and use could also be considered. The West and Southwest have experienced population growth in recent years, and second homes have also recently become popular in areas that were formerly primarily recreational. Anecdotal information suggests that home developments may be encroaching on areas of abandoned mines or mine wastes. In these cases, nearby populations may increase the potential use of these properties, with a concurrent increase in potential exposures.

The frequency of use may be related to their distance from roads. In other words, how remote are the mines? With the mines located on federal property, access may depend on fire roads or roads previously used during the mine's operation which are likely in disrepair so that access would be by foot, all terrain vehicles or possibly four-wheel drive vehicles. Some mines, however, may be located along well developed roads with easy access which may lead to more frequent visits or visits of longer duration.

7.2.3 Presence and Concentrations of Contaminants in Soils, Water, and Sediments

A major driver for the overall risk is the presence of contaminants. In the case of abandoned uranium mines, the contaminants would be both radioactive and stable metals. Radium, uranium, and possibly thorium could pose risks from external gamma exposures, but arsenic and other heavy metals (e.g., vanadium, selenium, copper, molybdenum) could pose a risk as well, especially to flora and fauna if there are enough waste materials. Some of the waste material quantities may be so minimal in area or volume that they do not pose a problem.

7.2.4 Density of Mines

One observation from this analysis is that the uranium mines are often along drainages where there can be a high density of mines or mine portals and associated wastes (see Figure 2.4 for example). While one mine may not pose a problem, a number of mines close together may increase the potential for adverse health or ecological effects, which may be seen at some distance from an individual mine site.

7.2.5 Level of Acceptable Risk

Lastly, the level of acceptable risk will also be important to determining how to prioritize the mines. The level of cancer risk typically used by EPA in the Superfund program is the risk range of 1 in 10,000 (10^{-4}) to 1 in 1,000,000 (10^{-6}) and the level of acceptable risk for non-carcinogens (i.e., some metals) is a hazard ranking less than 1. Sites which get frequent visitation may approach the upper end of the cancer risk range, while other sites would be at the lower end of the risk range. Residential exposure to uranium mine wastes, if it were to occur, would most likely be at the high end of risk range or even above.

The scoping analysis presented in this report indicates that at least some of the abandoned uranium mines have the potential to pose health and ecological hazards from both radioactive and non-radioactive materials. Data indicate that the concentrations of contaminants can be high enough to create adverse health effects if people were to spend substantial time on the sites. Non-radiological contaminants may be the most significant hazard, especially for flora and fauna. Since many of the sites are on federal lands, the largest exposure would be from recreational visits, or occupational use by a government employee or contractor, where the relatively short period of exposures would minimize the impact of high concentrations of contaminants. For the occasional visitor to abandoned mines, the mine wastes typically do not produce a significant radiation risk. However, individuals who visit a site frequently or for long periods of time can incur substantial risks. Residential exposure through on-site exposure or through the use of contaminated building material is not likely in most cases, except for some Tribal members, such as in the Navajo Nation, or other nearby residents. Where it does occur, the risks from these situations could be quite high.

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Appendix I. Swimming Risk

This appendix provides supplemental information on the swimming risks discussed in Chapter 3. Swimming risks were assumed to come from two sources; (1) ingestion and (2) immersion. In the drinking water discussion of Chapter 3 of the main report, we identified a recreational exposure scenario of 10 years of exposure, 14 days a year, and drinking 2 liters of water a day. For this recreational scenario, the lifetime cancer risk from drinking water contaminated with a range of uranium concentrations was in the 10^{-5} to 10^{-6} risk range. However, the analysis in Chapter 3 did identify that long-term use of pit-lake water could pose cancer risks. The potential hazard from the pit lakes may be greater from metals, such as arsenic, than from radionuclides. Since ingestion risks from ranges of radionuclide concentrations were discussed in Chapter 3, they are not discussed further here.

To calculate the immersion risks from exposure to radionuclides, we first calculated a dose using the formula modified from Whelan et al. (2006), and then applied a dose to risk coefficient from Tables 7.3 and 7.6 of Federal Guidance Report No. 13 (U.S. EPA 1999) to develop age-averaged site-specific cancer mortality and morbidity risk estimates. The formula for the immersion dose is as follows:

$$\text{swimming external dose} = Cw * EDFS * T \text{ exposure}$$

where Cw is the radionuclide concentration in the water in pCi/L, the EDFS is the External Dose Factor for Swimming in rem/hr per pCi/L, and the time of exposure is length of time a swimmer would be in the water in hours. To calculate the EDFS for the uranium and thorium decay series, we used the DCAL program (Eckerman et al. 2006), a comprehensive software system for the calculation of tissue dose and subsequent health risk from intakes of radionuclides or exposure to radionuclides present in environmental media. The results are listed below in Tables AI.1 and AI.2 for the U-238 and Th-232 decay series. Note that Ra-226 is included in the U-238 dose and risk calculations. The totals would apply if secular equilibrium were assumed; this is an unlikely case, because of the tendency for the radionuclides to settle into the sediment, as well as being dissolved in the water column. Table AI.3 shows the dose equivalent and risks per pCi/L for both decay series combined as a function of time spent immersed in the water.

In summary, the cancer risks from immersion due to swimming are very small per pCi/L from the U-238 and Th-232 decay series. Even if secular equilibrium were assumed and all the radionuclides in either series were present, the cancer risks from immersion while swimming are negligible for the recreational scenario, even at concentrations of 10s to 100s of pCi/L. The cancer risks from ingesting water while swimming are also anticipated to be low, based on the drinking water discussion in Chapter 3 of the main report.

Table AI.1. Uranium-238 Dose Equivalent Rate and Risk per pCi/L per hour (EDFS): Water Immersion

Nuclide	Dose Equiv. Rate [(rem/hr) per (pCi/L)]	Mortality Risk[1]	Morbidity Risk
U-238	7.8E-14	4.5E-17	6.6E-17
Th-234	8.8E-12	5.0E-15	7.4E-15
Pa-234m	2.7E-11	1.5E-14	2.2E-14
Pa-234	2.5E-09	1.4E-12	2.1E-12
U-234	1.9E-13	1.1E-16	1.6E-16
Th-230	4.5E-13	2.6E-16	3.8E-16
Ra-226	8.3E-12	4.8E-15	7.1E-15
Rn-222	5.1E-13	3.0E-16	4.3E-16
Po-218	1.2E-14	7.0E-18	1.0E-17
At-218	3.0E-12	1.7E-15	2.5E-15
Pb-214	3.2E-10	1.8E-13	2.7E-13
Bi-214	2.1E-09	1.2E-12	1.8E-12
Po-214	1.1E-13	6.3E-17	9.3E-17
Pb-210	1.4E-12	8.0E-16	1.2E-15
Bi-210	4.0E-12	2.3E-15	3.4E-15
Po-210	1.1E-14	6.5E-18	9.5E-18
Total	**5.0E-09**	**2.9E-12**	**4.2E-12**

Table AI.2. Thorium-232 Dose Equivalent Rate per pCi/L per hour(EDFS): Water Immersion

Nuclide	Dose Equiv. Rate [(rem/hr) per (pCi/L)]	Mortality Risk	Morbidity Risk
Th-232	2.20E-13	1.26E-16	1.86E-16
Ra-228	0.00E+00	0.00E+00	0.00E+00
Ac-228	1.29E-09	7.44E-13	1.10E-12
Th-228	2.41E-12	1.39E-15	2.04E-15
Ra-224	1.25E-11	7.21E-15	1.06E-14
Rn-220	5.00E-13	2.87E-16	4.23E-16
Po-216	2.24E-14	1.29E-17	1.89E-17
Pb-212	1.82E-10	1.05E-13	1.54E-13
Bi-212	2.54E-10	1.46E-13	2.15E-13
Po-212	0.00E+00	0.00E+00	0.00E+00
Tl-208	4.86E-09	2.80E-12	4.11E-12
Total	**6.61E-09**	**3.80E-12**	**5.59E-12**

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[1] Mortality risk is 5.575 E-4 per rem; Morbidity risk is 8.46 E-4 per rem.

Table AI.3. Total Dose Equivalent and Risk per pCi/L per hour (EDFS): Water Immersion

Time Spent Swimming (hours)	Dose Equivalent (rem per pCi/L)	Mortality Risk (per pCi/L)	Morbidity Risk (per pCi/L)
1	1.2E-08	6.5E-12	9.8E-12
2	2.3E-08	1.3E-11	2.0E-11
3	3.5E-08	1.9E-11	2.9E-11
4	4.6E-08	2.6E-11	3.9E-11
5	5.8E-08	3.2E-11	4.9E-11
10	1.2E-07	6.5E-11	9.8E-11
15	1.7E-07	9.7E-11	1.5E-10
20	2.3E-07	1.3E-10	2.0E-10
25	2.9E-07	1.6E-10	2.5E-10
30	3.5E-07	1.9E-10	2.9E-10
40	4.6E-07	2.6E-10	3.9E-10
50	5.8E-07	3.2E-10	4.9E-10
75	8.7E-07	4.9E-10	7.4E-10
100	1.2E-06	6.5E-10	9.8E-10

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Appendix II. Calculation of Slope Factors for Naturally Occurring Radionuclides

In developing the target soil screening levels found in Chapter 3 of this report, the slope factors for external exposure to, ingestion of, and inhalation of soil at an infinite depth must be considered. This appendix calculates the slope factors for the naturally occurring radionuclides under consideration. The Radionuclide Table, Radionuclide Carcinogenicity, formerly the Health Effects Assessment Summary Tables or HEAST Tables (http://www.epa.gov/radiation/heast/index.html), lists slope factors for individual radionuclides or for decay chains consisting of a parent nuclide and its short-lived progeny (i.e., radioactive daughter products with half-lives of less than 6 months). As explained below, naturally occurring radionuclides are often associated with their long-lived decay products. The slope factors for three naturally occurring radioactive decay series—natural uranium, Ra-226, and Th-232—used in the present report include the contributions from these decay products. This appendix explains the methodology used to calculate these combined slope factors.

The following guidance is excerpted from U.S. EPA 1996a:

> *Selected radionuclides and radioactive decay chain products are designated with the suffix "+D" (e.g., U-238+D, Ra-226+D, Cs-137+D) to indicate that cancer risk estimates for these radionuclides include the contributions from their short-lived decay products, assuming equal activity concentrations (i.e., secular equilibrium) with the principal or parent nuclide in the environment.*
>
> . . . .
>
> *Note that there may be circumstances, such as long disposal times or technologically enhanced concentrations of naturally occurring radionuclides, that may necessitate the combination of the risks of a parent radionuclide and its decay products over several contiguous subchains. For example, Ra-226 soil analyses at a site might show that all radium decay products are present in secular equilibrium down to stable Pb-206. In this case, Ra-226 risk calculations should be based on the ingestion, inhalation and external exposure slope factors for the Ra-226+D subchain, plus the ingestion, inhalation and external exposure factors for the Pb-210+D subchain.*

Radium-226 slope factors for the external exposure, soil ingestion, and inhalation pathways used in this analysis were calculated according to the guidance cited above. The same logic was applied to Th-232, whose progeny includes Ra-228, which has a half-life of 5.75 y, and Th-228, with a half-life of 1.91 y. Since the naturally-occurring thorium at the uranium mines will be in equilibrium with this progeny, the thorium slope factors are calculated as the sum of the slope factors for Th-232, Ra-228+D, and Th-228+D that are listed in the HEAST tables. Natural uranium is assumed to consist of U-234, U-235, and U-238, in ratios corresponding to natural isotopic abundances. We first calculated a slope factor for the U-238 decay series, which we will call U-238$_{series}$, by taking the sum of the slope factors for U-238+D, U+234, and Th-230. Radium-226 was not included, because separate soil analyses are normally performed for radium which, due to its different chemical properties, is often not in equilibrium with uranium. In

AII-1

similar fashion, we calculated a slope factor for the U-235 decay series (U-235$_{series}$) as the sum of the slope factors for U-235+D, Pa-231, and Ac-227+D. We then calculated slope factors for natural uranium, by multiplying the slope factor for the U-235 decay series by the ratio of the specific activities of U-235 to U-238 and adding this product to the slope factor for the U-238 decay series, as shown by the following expression:

$$Unat = U\text{-}235_{series} \times f_{235} + U\text{-}238_{series}$$

where f_{235} is the ratio of the specific activities of U-235 and U-238 in natural uranium and is shown in the following expression:

$$f_{235} = \frac{[U-235]}{[U-238]} = 0.046$$

Because uranium concentrations in soil are commonly reported as pCi/g of U-238, the natural uranium slope factors are normalized to a unit activity concentration of U-238. To apply these slope factors, multiply by the actual activity of U-238, not the total activity of the uranium isotopes.

Details of these calculations are shown in the Table AII-1 below.

Table AII-1. Calculation of Slope Factors for NORM Decay Series

Series	Nuclide	Activity Fraction	SF		
			External (risk/y per pCi/g)	Ingestion (risk/pCi)	Inhalation (risk/pCi)
U-Series	U-238+D	1	1.14E-07	2.10E-10	9.35E-09
	U-234	1	2.52E-10	1.58E-10	1.14E-08
	Th-230	1	8.19E-10	2.02E-10	2.85E-08
	U-235+D	0.046	5.43E-07	1.63E-10	1.01E-08
	Pa-231	0.046	1.39E-07	3.74E-10	4.55E-08
	Ac-227+D	0.046	1.47E-06	1.16E-09	2.09E-07
	Total[a]		2.14E-07	6.48E-10	6.14E-08
Ra-Series	Ra-226+D	1	8.49E-06	7.30E-10	1.16E-08
	Pb-210+D	1	4.21E-09	2.66E-09	1.39E-08
	Total		8.49E-06	3.39E-09	2.55E-08
Th-Series	Th-232	1	3.42E-10	2.31E-10	4.33E-08
	Ra-228+D	1	4.53E-06	2.29E-09	5.23E-09
	Th-228+D	1	7.76E-06	8.09E-10	1.43E-07
	Total		1.23E-05	3.33E-09	1.92E-07

[a] Sum, weighted by fractional activities

U.S. EPA (U.S. Environmental Protection Agency). n/d. "Radionuclide Table: Radionuclide Carcinogenicity – Slope Factors" http://www.epa.gov/radiation/heast/docs/heast2_table_4-d2_0401.pdf

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Appendix III. Occupational and Public Risks Associated with In-Situ Leaching

Introduction

EPA's Science Advisory Board (SAB) recommended that EPA present information on in situ leaching (ISL) mining operations and uranium mill operations to provide a more complete picture of uranium production. While this report focuses on the impacts associated with conventional surface and underground uranium mines, it provides limited background materials, in this and other appendices, on risks associated with uranium milling and ISL operations and wastes generated by those processes, even though they may not be considered TENORM by virtue of their regulation by the NRC and its Agreement States under the Atomic Energy Act and its amendments.

The NRC stated its intent in July 2007 (NRC 2007b) to develop a Generic Environmental Impact Statement (GEIS) on uranium milling which would provide more detailed information on the ISL process and impacts, and may include more recent information on the impacts. The reader is referred to that document when made available to the public in the future for additional background information and associated risk assessment.

This appendix summarizes information on environmental and health-related aspects of ISL operations. The primary sources used for this review are, *Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining. Volume 1: Mining and Reclamation Background* by U.S. EPA (2006), *An Environmental Overview of Unconventional Extraction of Uranium* by Marlowe (1984) and *A Baseline Risk-Informed Performance Approach for In Situ Leach Uranium Extraction Licensees* by Mackin et al. (2001).

Background

In situ leaching is an extraction process that is regulated by the NRC or its Agreement States; the waste materials and fluids are considered byproduct material (see Appendix VI of U.S. EPA 2006). However, these operations are subject to the requirements of UMTRCA implemented by EPA regulations 40 CFR Part 192 and subsequently by NRC's regulations in 10 CFR Part 40. While ISL operation wells are subject to permitting under EPA's Underground Injection Control (UIC) program (U.S. EPA 2006, Appendix VI), the restoration requirements are considered complementary to those of UMTRCA, which take precedence. ISL operations, also known within the uranium industry as "in situ recovery," or ISR, are discussed here to provide a more complete representation of the impacts from uranium production. The following several points assume that ISL is economic.

ISL is used when environmental conditions are favorable, such as the following:

- The ore body is located in a saturated, permeable formation that is confined hydrologically both above and below
- The ore body is chemically amenable to the ISL process
- The uranium is present in multiple-layered roll fronts that may be offset by faulting

- The ore grade is low, and the ore body is too thin to mine by conventional means, however, if the ore body is too thin then even ISL may not be geologically possible

In this method of extraction, uranium ores are leached underground by the introduction of a solvent solution, called a lixiviant, through injection wells drilled into the ore body. The process does not require the physical extraction of ore from the ground, which makes it a much more economical option in many cases. Lixiviants for uranium mining commonly consist of water containing added oxygen and carbon dioxide or sodium bicarbonate, which mobilize uranium. Other ISL facilities, especially in Eastern Europe, employ an acid-based lixiviant, though this method is rarely, if ever, utilized in the United States. The lixiviant is injected, passes through the ore body, and mobilizes the uranium. The uranium-bearing solution is pumped to the surface from production wells.

The pregnant leach solution is processed to extract the uranium, usually by ion exchange or by solvent extraction. The ion exchange process employs a resin that, once fully saturated with uranium, is flushed with a highly concentrated salt (e.g., sodium chloride) solution. This reverses the exchange process and releases uranium into the solution. The uranium solution is then sent to another process for concentration, precipitation, and drying as yellowcake. The solvent extraction process relies on unmixable properties between the pregnant leach solution and (uranium) solute. Normally, the solvents are organic compounds that can combine with either cationic or anionic solutes. For example, anionic solutions include amine chains and ammonium compounds, and cationic solutions are phosphoric acid-based. Figure AIII-1 shows a simplified version of the ISL process.

Figure AIII-1. Illustration of ISL Process

This figure shows a simplified version of how ISL solution mining works. Lixiviant is injected into the ground through wells on the left and far right, the fluid flows underground, dissolving uranium and carrying it in solution until it reaches a production well in the center. The fluid carrying dissolved uranium is returned to the surface from the production well, and piped to a production facility for refinement into yellowcake.
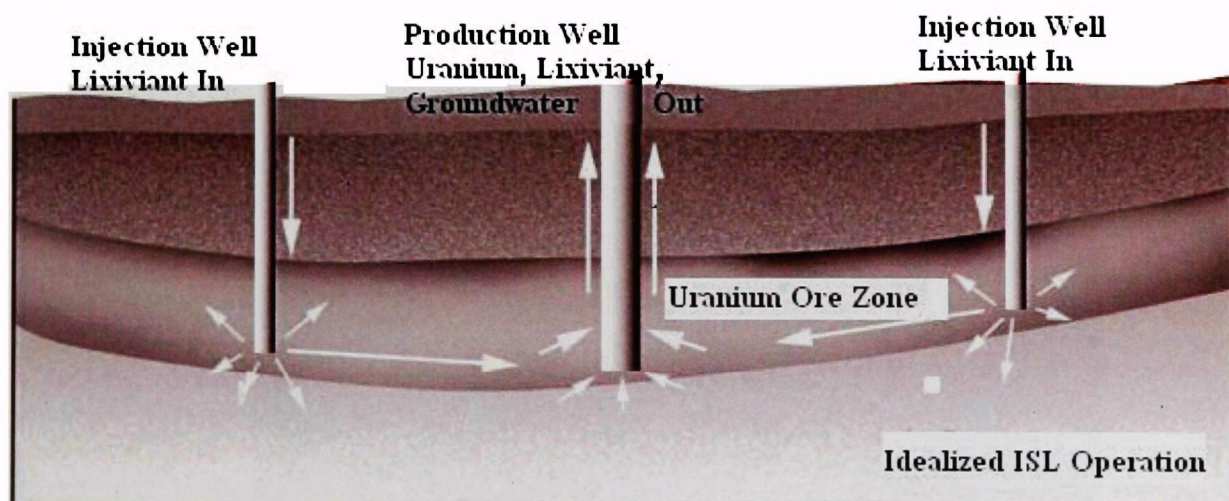
Source: Modified after ANAWA : http://www.anawa.org.au/mining/isl-diagram.html

When the ISL process is completed, the ore body and aquifer are placed in a restoration phase, as required by mine permits, NRC and Agreement State regulatory programs. Typically, the aquifer

must be restored to background or EPA drinking water maximum contaminant limit levels where possible or practical, or to Alternate Concentration Limits (ACLs) in terms of the presence of metals, organics, pH level, and radioactivity, approved by the NRC and its Agreement States. Therefore, in some cases, restoring it to the pre-operation level does not necessarily make it potable. EPA groundwater protection standards issues under authority of UMTRCA are required to be followed by ISL licensees of the NRC and its Agreement States. In addition to those requirements, ISL operators must apply for UIC permits from EPA. Through the UIC aquifer exemption process, EPA and its Delegated States determine if an aquifer or part of an aquifer is exempt from protection as an underground source of drinking water during the mining process. Approval of this exemption is necessary before a UIC permit may be issued for ISL mineral extraction wells. EPA requires, however, that non-exempted groundwater sources be protected from contamination. The UIC requirements are complementary to UMTRCA requirements and do not override the necessity for a licensee to take measures to restore well field groundwater.

According to Commission Order CLI-00-22, in situ leach mining (ISL) produces two categories of waste; (1) gaseous emissions and airborne particulates resulting from drying of yellowcake (which could take place at an off-site facility), and (2) liquid waste associated with operations including well field processing and aquifer restoration (Dicus et al. 1999). A variety of methods exist to address liquid waste disposal and storage at ISL facilities, including the use of evaporation ponds, deep-well injection, land application, and surface discharge under a National Pollution Elimination System (NPDES) permit.

Figure AIII-2. Picture of an in situ leach field
Unlike a conventional mine, ISL operations produce minimal solid waste. This picture from the Wyoming Association web site shows an ISL well field.

Source: http://www.wma-minelife.com/uranium/insitu/insitufr.htm

While the primary environmental concern from ISL operations may be related to groundwater, Mackin et al. (2001) identify four primary risks from ISL operations in three categories:

   (i)   Surface environment chemical hazards
   (ii)   Surface environment radiological hazards
   (iii) Groundwater chemical and radiological contamination hazards

The main risks to the worker are from the surface chemical and radiological hazards associated with various types of accidents at the site. Conversely, the risks to the general public pertain to the contamination of drinking water sources. Therefore, site-specific accidents would not affect the public unless a large prolonged release of hazardous chemicals and/or radionuclides were allowed to contaminate the local water supplies. In addition to hazards during ISL operation, site rehabilitation presents environmental and health concerns. Each of these issues is discussed in the sections to follow.

<u>(i)   Surface Environment Chemical Hazards (Mackin et al. 2001):</u>

Twelve chemicals are commonly used in ISL operations and could pose hazards to ISL workers, but are unlikely to affect the general public. These chemicals, along with their intended purpose at ISL facilities, are summarized below in Table AIII-1. Potential hazardous situations involving each of these chemicals are discussed in the paragraphs following the table.

Table AIII-1: Typical Chemicals Found at ISL Operations

Chemical	Formula	Purpose at ISL Operations
Anhydrous Ammonia	NH_3	pH adjustment during uranium precipitation phase
Sulfuric Acid	H_2SO_4	Used to separate the uranium from the carbonate complex pumped from below the surface
Oxygen (gaseous and liquid)	O_2	Oxidant added to lixiviant used for extraction of uranium forming UO_3
Hydrogen Peroxide	H_2O_2	Oxidant used during the precipitation phase of uranium
Sodium Hydroxide	NaOH	pH adjustment during radium removal phase
Barium Chloride	$BaCl_2$	Used as a precipitant for radium during restoration and wastewater treatment
Carbon Dioxide	CO_2	Carbonate used to keep oxidized uranium in solution, also used for pH adjustment of lixiviant
Hydrochloric Acid	HCl	pH adjustment during radium precipitation phase
Sodium Carbonate	Na_2CO_3	Carbonate used to keep oxidized uranium in solution, also used in the regeneration/recycling resin
Sodium Chloride	NaCl	Used to regenerate/recycle the resin for further use in uranium extraction
Hydrogen Sulfide	H_2S	Used in groundwater restoration to decrease the solubility of various heavy metals
Sodium Sulfide	Na_2S	Used in groundwater restoration to decrease the solubility of various heavy metals

The main hazard posed by ammonia would be if a pipe were to break inside the processing plant. The liquid ammonia, assumed to be under high pressure, would likely have a significant spray in such an event and would pose a risk to the skin and eyes of any localized worker. In addition, as the ammonia quickly evaporates, an inhalation hazard would exist that would be exacerbated by poor ventilation. The possibility also exists for a leak in the primary holding tank or associated piping which transfers the ammonia from outside the plant to its application site.

Similar to ammonia, a break in the pipes used to transfer sulfuric acid, sodium hydroxide, and hydrochloric acid inside the plant would pose a hazard, as it is highly corrosive to the skin. Sulfuric acid and sodium hydroxide would not pose a significant inhalation hazard unless the ventilation systems in the plant were not in operation or if a worker encountered a "spray" caused by smaller leaks in the piping system. A hydrochloric acid leak could lead to a vapor inhalation hazard, especially in confined spaces. These chemicals are also highly reactive with one another and so multiple localized failures, as might be the case with fire or explosions, would cause an even greater hazard.

Oxygen gas poses a significant hazard because of its combustible properties. Similarly, hydrogen sulfide and sodium sulfide also pose risks because of their flammable properties, in addition to an inhalation as well as an eye/skin irritation hazard.

Hydrogen peroxide's main risk pertains to the degradation of the chemical into hydrogen and oxygen gas which can be caused by mechanical shock, incompatible materials, light, ignition sources, excess heat, strong oxidants, rust, dust, or a pH greater than 4.0. Also, if the chemical is contained within an especially rigid tank, the casual degradation of the H_2O_2 into water and oxygen gas would cause expansion which could rupture the holding tank. A pipe failure event within the processing plant holds similar risks to that of ammonia and sulfuric acid.

Barium chloride is only considered a hazard if it is inhaled or ingested. Since the chemical is in solution form at an ISL plant, this would only become significant if the worker encountered a "spray" from a leaky piping system. Carbon dioxide from a leak can pose a risk of asphyxiation if it occurs in a sufficiently confined space. This can be avoided if a self-contained breathing apparatus were used when entering confined spaces where the displacement of oxygen with carbon dioxide is possible.

Sodium chloride and sodium carbonate both are very irritating to the eyes and the skin. In addition, sodium carbonate can pose an inhalation hazard when it is in its salt stage (dust inhalation) or from small leaks which form a spray of the sodium chloride/carbonate solution. Sodium carbonate also reacts readily with HCl and H_2SO_4.

(ii)   Radiological risks

Thickener Tank Failure

The thickener tank stores wet yellowcake slurry before it is sent to a precipitation operation and dried into U_3O_8 yellowcake. Thickener tank failure can pose an inhalation risk to workers if

spills are not cleaned up before the contaminants are allowed to dry. This accident scenario would not be a significant risk to off-site residents.

The thickener tank itself does not pose any external exposure risk, as most of the uranium progeny have been removed and the alpha component would be significantly attenuated by the slurry. Annual external exposures have been calculated to be 120 mrem for the limiting case of a worker standing directly next to the thickener tank for an entire 2,000 hour work year (Mackin et al. 2001).

If the yellowcake slurry is allowed to dry after a spill incident, it would pose a significant risk of uranium inhalation. Conservative treatments indicate that the dose to the public from a massive spill and subsequent airborne contamination event remain below the radiation dose limits established by 10 CFR 20 for members of the general public, however, the intake to an unprotected worker has the potential to exceed the 5 rem annual occupational limits (Mackin et al. 2001).

Yellowcake Dryer Accident

As discussed above, the dried yellowcake which consists of quantities of U_3O_8, can pose a significant inhalation hazard to the onsite worker when it is allowed to dry. Failure of the dryer cake systems can stem from a number of accidents, including fire/explosion (worst case), spill over of dryer contents due to a faulty discharge valve, failure of offgas treatment systems causing the gases to release into the dryer area, and damage to the facility via natural disasters. It is important to note that the failure of the yellowcake dryer systems due to natural disasters is effectively bounded by the fire and explosion scenario. Exposures from a yellowcake dryer accident would presumably be of similar magnitude to that of the thickener tank scenario. (Mackin et al. 2001)

Exposure to Pregnant Lixiviant or Loaded Resin

Pregnant lixiviant and loaded uranium resin may pose a radiological hazard as an external exposure source, and present the possibility of inhaling elevated levels of radon-222. The most likely indoor exposure incident would occur if the pregnant lixiviant/resin were released due to a pipe or valve failure during the ion-exchange process, at which point the solution would drain from the ion-exchange column and the radon gas would be released to the air.

In addition to the inhalation hazard from radon, the pregnant lixiviant contains some other radioisotopes of interest that may also cause a significant exposure. These radioisotopes are shown in Table AIII-2, along with typical activity concentrations (Mackin et al. 2001).

Table AIII-2: Radionuclides with Typical Activity Concentrations* found in Pregnant Lixiviant/Loaded Resin

Radionuclide	Activity Concentration (pCi/L)
^{222}Rn	8.0×10^5
^{226}Ra	3.4×10^3
Natural Uranium (^{234}U, ^{235}U, ^{238}U)	1.7×10^5
^{218}Po	3.4×10^3
^{214}Bi	3.4×10^3
^{214}Po	3.4×10^3

*Progeny assumed to be in equilibrium

Conservative treatments of a possible spill incident have been modeled to show that a maximum annual exposure would be 27 mrem to a subject standing on a spill of infinite area and depth; with the consideration of loaded resin, this value becomes much lower. Since such a spilling event would likely be cleaned up expeditiously, such an exposure is not likely and is also well within the limits established in 20 CFR 20 for the general public, as well as the site worker (Mackin et al. 2001).

Exposures from the failure of near surface piping and subsequent runoff into containment ponds can also pose a possible hazard to workers. It is likely that the inhalation component in this scenario is negligible due to the dilution of the radon gas releases by ambient air; however, the external component would be similar to the indoor scenario previously described. See the next section for further discussion of outdoor near-surface releases.

(iii)   <u>Groundwater Contamination Risks</u>

Due to the nature of the ISL process (specifically the low pH and oxidation mechanisms), other heavy metals and hazardous elements are also mobilized from the ore and can contaminate the groundwater. These elements include the radioisotopes and progeny of uranium, thorium, radium, and radon, as well as the non-radioactive elements such as arsenic, vanadium, zinc, selenium, and molybdenum (for a more complete list see Table AIII-3). Because these elements become mobilized in the target aquifer by the process of uranium extraction, it is possible for them to migrate out of the ore body into surrounding aquifers which might feed the local water supply. The underground propagation of this contamination into surrounding water is known as an excursion. Horizontal excursions refer to the lateral movement of the water, while vertical excursions indicate contamination of aquifers above and below the target ore body.

In order to detect and minimize this process, ISL facilities drill monitoring wells outside of the main well-field at a distance sufficient to detect any excursion events, while minimizing any erroneous indicators as a result of normal fluctuations. Horizontal excursions are more common than vertical excursions, but do not often become problematic to the outside water supply as long as they are detected and cleaned up within a reasonable time period. Vertical excursions are generally a result of well casing failure (ineffective cementing of well casing), improper sealing of abandoned exploration wells, or discontinuous or permeable natural confinement layers. Similar to horizontal excursions, vertical excursions do not pose a significant threat unless allowed to persist over significant periods of time—this is unlikely if geological properties of the

confinement layers are accurately characterized (to prevent downward vertical excursions), and the well shafts are effectively cased and proper monitoring well stations have been established. Along with well monitoring techniques, general practice at ISL facilities is to limit the injection of lixiviant so that it is always slightly less in volume than the product solution that is pumped out of the aquifer. This operating policy, known as "process bleed," would effectively preclude excursions caused by overloading the aquifer, and the subsequent expansion and redistribution of the water.

In the United States, excursions have been frequently detected by the monitoring wells located around the well field. One of the more infamous and environmentally problematic ISL operations was located at Irigary, Wyoming. This facility was plagued by persistent environmental excursions which began in mid-March of 1979, and were not brought under control until early July of that same year. The Wyoming Department of Environmental Quality reported that these excursions were a result of the neglect of injection pressure monitoring as well as testing the integrity of the well casings (Mudd 1998). Another significant example is the Bruni mine in Texas, where there was a continued problem with both leachate spills and excursions. The Texas Department of Water Resources reported that at one point during the operational period the Bruni mine was cited for fourteen excursion incidents, while only five had originally been reported (Mudd 1998). Despite these scenarios, no significant contamination of local water supplies has been reported as a result of these excursions.

A separate technical analysis of excursions in early Texas and Wyoming ISL facilities (Staub et. al 1986) provides a more detailed review of the horizontal and vertical groundwater impacts from those facilities. In that study, concern was greatest in instances where a near surface aquifer had been polluted by vertical pollution from surface evaporation ponds, unplugged exploration boreholes, and improperly constructed injection/production wells. The associated impacts were greatest due to use of such water bodies by livestock or humans, and the difficulty and expense of aquifer restoration.

In addition to the below ground excursion incidents, the groundwater can become contaminated due to failure of the near-surface or surface piping systems which transfer the pregnant lixiviant from the well field area to the processing facility. Typical activity concentrations for the radionuclides present in lixiviant are given in Table AIII-2. In addition, Table AIII-3 displays the maximum measured concentrations of non-radioactive contaminants in pregnant lixiviant based on a survey of available licensing documents (Mackin et al. 2001). Once the pregnant lixiviant solution is released, there are three potential outcomes for the contamination; runoff into surface bodies of water, absorption into the soil and possible subsequent infiltrations of the groundwater, or runoff into a surface pond designed to prevent groundwater contamination. The first two scenarios show the possibility for contamination of drinking water sources and would have an obvious environmental impact if not dealt with in a timely fashion. The third scenario poses a possible radiological hazard for workers at the site and is discussed in Section ii of this appendix.

Table AIII-3. Maximum Measured Non-radioactive Contamination in Pregnant Lixiviant

Contaminant	Concentration (mg/L)	Contaminant	Concentration (mg/L)
Arsenic	0.3	Barium	0.6
Boron	0.2	Cadmium	0.01
Chloride	1,800	Chromium	0.03
Copper	0.04	Flouride	1
Iron	0.02	Lead	0.01
Manganese	6	Mercury	<0.0001
Molybdenum	62	Nickel	0.09
Nickel	0.09	Nitrate	1
Selenium	5	Silver	<0.01
Sulfate	1,200	Total dissolved solids	5,500

(iv)   Post-Operation Site Restoration and Rehabilitation

There are two main methods employed to restore the contaminated aquifer back to its preoperational conditions. In general, the first method employed is termed "groundwater sweep," and involves pumping out the equivalent volume of groundwater from the mined aquifer and replacing it with fresh uncontaminated water. The volume of water pumped out of the mined ore zone is known as the "pore volume." The pore volume can then be moved to an evaporation pond to remove the water and then dispose of the residual wastes. An alternate disposal of the pore volume is to inject the water through wells permitted through EPA's SDWA UIC program into much deeper aquifers designated for waste disposal. In this case, the increased levels of contaminant should not affect neighboring aquifers or potential drinking water sources. This method has proven to be useful at the beginning stages of the restoration process. However, because of the heterogeneous properties of the ore zone aquifer, complete restoration of the mining site by this technique alone is not economical. Furthermore, many site locations do not have the resources for the large amount of clean groundwater that is required for an extensive groundwater sweep operation.

The second technique that can be employed is treating the contaminated pore volume via reverse osmosis. Here, the water is pumped out of the ore zone and passed through a reverse osmosis membrane at high pressure. This process separates the aquifer water into a highly concentrated liquid contaminant and a clean water volume known as the reverse osmosis (RO) permeate. The RO permeate is then recirculated into the ore zone using alternating pumping wells to effectively flush the heterogeneously distributed lixiviant present in the aquifer. The benefits of reverse osmosis are that no outside source of groundwater is needed to replace the pumped pore volume, since the volume is being treated and re-injected into the depleted ore zone. In practice, this method can only be employed after groundwater sweeping, because the high concentrations of contaminants during the initial stages of the restoration process tend to disrupt the RO membranes (Davis and Curtiss 2005).

Chemicals such as hydrogen sulfide or sodium hydrosulfide may also be added to the re-injected water during the later stages of restoration to achieve a state of "chemically reducing conditions." The effect of these chemicals is to decrease the solubility of several contaminating

metals that are of concern, including uranium, selenium, arsenic, and molybdenum. However, there are other contaminants, such as radium, which remain mobile under chemically reduced conditions. Barium chloride is often used to precipitate radium out of waste water and can also be used during aquifer restoration to mitigate the effect of radium contamination (Mackin et al. 2001).

Despite these efforts at returning the mining site to its original preoperational state, it has been very difficult to achieve complete site rehabilitation. Not all of the contamination can be removed because lixiviant will be present in sections of the aquifer that are in areas of lower porosity. The efforts to create a chemically reduced condition to render the heavy metals insoluble may not apply to all contaminants of interest. Furthermore, achieving complete rehabilitation of the site is very time consuming and costly. New technologies, including bioremediation, may potentially improve the restoration of groundwater and wastewater impoundments (Rio Tinto 2007). The surface facilities and groundwater must be reclaimed in accordance with EPA requirements for radiation and environmental protection in 40 CFR 192 (see Volume I).

Summary

In situ leaching for uranium poses several possible environmental and health-related concerns. Through the extraction and processing of uranium ore into yellowcake, many hazardous chemicals and radionuclides are utilized or concentrated which, coupled with certain accident scenarios, can pose significant risk to workers at these facilities. From a radiological standpoint, risks are mainly significant to on-site workers, and have been shown to be minimal for the public (Mackin et al. 2001). From a hazardous chemical standpoint, the immediate concern is for on-site workers; however, the risk to the public can become significant if a prolonged release of hazardous material is allowed to contaminate nearby drinking water sources.

The leaching process poses the risk of contaminating neighboring aquifers which, in turn, might affect significant water supply sources. This can happen through horizontal and vertical excursions below the surface, or from events such as pipe failure on or near the surface. The risk of excursions is mitigated by the inclusion of vertical and horizontal monitoring wells located around the perimeter of the ore zone, as well as the operational practice of "process bleeding." The wells are designed to detect excursions in a short period of time, so that corrective actions and cleanup operations can take care of the problem before the water sources outside of the mining site are significantly degraded.

Finally, in situ leaching poses a problem from a restoration standpoint. Although there are multiple techniques to restore the mined aquifer to its preoperational state, in many cases the lixiviant can never be completely purged from the site. Attempts to bring the aquifer to a chemically reduced state cannot account for all types of contaminants, and the entire rehabilitation process is both expensive and time consuming.

References:

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Rio Tinto 2007--Rio Tinto Energy America. Comments on the Environmental Protection Agency's *Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining Volume 2: Investigation of Potential Health, Geographic and Environmental Issues of Abandoned Uranium Mines.*

Staub et al. 1986--Staub, W., Hinkle, N., Williams, R., Anastasi, F., Osiensky, D., and Rogness, D. *An analysis of Excursions at Selected In Situ Uranium Mines in Wyoming and Texas.* NUREG/CR-3967 and ORNL/TM-9956, Oak Ridge National Laboratory and University of Idaho. Prepared for U.S. Nuclear Regulatory Commission. July 1986.

U.S. EPA 2006--U.S. EPA (U.S. Environmental Protection Agency). *Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining. Volume 1: Mining and Reclamation Background.* EPA 402R-05-007, Washington, DC: U.S. EPA, 2006.

Appendix IV. Risks Associated with Conventional Uranium Milling Operations

Introduction

Although uranium mill tailings are considered byproduct materials under the AEA and not TENORM, EPA's Science Advisory Board (SAB) recommended that EPA present information on uranium mill operations, as well as *in situ* leaching (ISL) mining operations, to provide a more complete picture of uranium production. While this report focuses on the impacts associated with conventional surface and underground uranium mines, it provides limited background materials, in this and other appendices, on risks associated with uranium milling and ISL operations and wastes, generated by those processes, even though they may not be considered TENORM by virtue of their regulation by the NRC and its Agreement States under the Atomic Energy Act and its amendments.

The NRC stated its intent in July 2007 (NRC 2007b) to develop a Generic Environmental Impact Statement (GEIS) on uranium milling which would provide more detailed information and may include more recent information on the impacts of uranium milling. The reader is referred to that document when made available to the public in the future for additional background information and associated risk assessment.

This appendix summarizes information on environmental and health aspects of uranium mill operations. The primary sources used for this review are *"Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining. Volume 1: Mining and Reclamation Background"* by U.S. EPA (2006), *"Final Generic Environmental Impact Statement on Uranium Milling Volume 1 and 2"* by U.S. NRC (1980), *"Final Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 192) Volume 1"* by U.S. EPA (1983), and *"Uranium Mining and Milling Wastes - An Introduction,"* by Peter Diehl of the WISE Uranium Project (2004).

Background

Uranium milling is the process of converting raw ore as it arrives from mining operations into a product known as uranium yellowcake. The raw uranium ore and resultant yellowcake are shown in Figure AVI-1, and a generalized schematic of a typical milling process is shown in Figure AVI-2.

The first steps in the milling process involve crushing and grinding the ore in order to obtain smaller, uniform particle sizes throughout. Often, water is added during this stage to control dust, or lixiviant may also be added to facilitate the extraction process. Screens separate fine particles, which continue to the next stage in the milling process, from coarse particles, which are recirculated in the milling circuit. Dust that is not sufficiently suppressed by the addition of water/lixiviant is generally collected by air pollution control mechanisms, which return the fugitive particles to the milling process.

Once the ore is ground into uniform small particles, the processed ore moves to the leaching stage. In the most common leaching method, known as "acid leaching", uranium is removed from the processed ore with sulfuric acid. Sodium chlorate is also added as an oxidizing agent to improve the

solubility of the uranium. An alternative approach is alkaline leaching, which is preferable when the raw ore contains a significant portion of limestone (greater than 12%), because the acid leaching process then requires uneconomically large amounts of acid to be effective. Alkaline leaching, however, requires much finer grinding of the ore in comparison to acid leaching. Both methods of leaching have similar environmental and health impacts; however, the waste produced from acid leaching is generally more mobile and will be used as the bounding scenario in this treatment (U.S. EPA 1983).

Figure AIV-1. Raw Uranium Ore and Yellowcake Product
This figure shows the incoming raw uranium ore as it enters the uranium milling process (left), as well as the final product of uranium yellowcake (right)

Source: http://www.eoearth.org/upload/thumb/c/c1/Uranium_ore_square.jpg (left)
http://www.eia.doe.gov/kids/energy_fungames/energyslang/images/yellowcake1.jpg (right)

Figure AIV-2. Generalized Uranium Mill Physical Layout

This figure shows how a uranium mill is physically set up to crush raw ore into particles amenable to chemical treatments for extracting uranium.
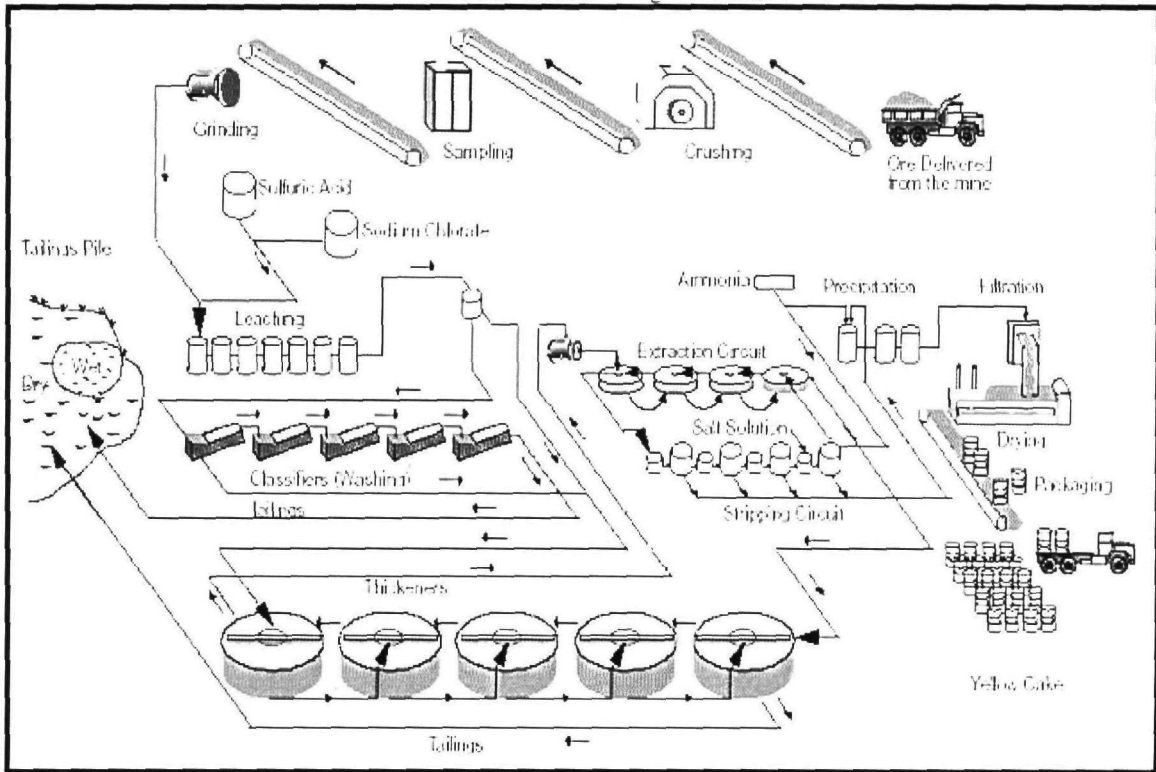
Source: http://www.eia.doe.gov/cneaf/nuclear/page/uran_enrich_fuel/uraniummill.html

After the leaching stage, the pregnant lixiviant generally contains about 50-60% solids. These solids, called "tailings," are filtered out and sent to on-site tailings piles or impoundments in the form of sands and slimes. Once most of the solids have been removed, the filtered lixiviant is transferred to an extraction circuit where the desired uranium is stripped from the pregnant lixiviant, followed by a precipitation and drying process, which produces the desired yellowcake product.

Potential Environmental and Health Issues from Mill Tailings

The wastes produced during the milling process and stored in tailings impoundments are the principal source of milling-related health and environmental hazards. Typical properties of these mill tailings are shown in Table AIV-1. During the milling process, nearly 90% of the uranium contained in the ore is removed, and so the primary radiological concern is the remaining progeny associated with uranium such as thorium, radium, radon, and lead. The actual activity of these uranium progeny can vary depending on the specific methods employed,; however, as much as 50-86% of the original activity of the ore is retained in the mill tailings (U.S. EPA 2006). Hazardous stable elements are also extracted from the ore and transferred to the tailings piles, including arsenic, copper, selenium, vanadium, molybdenum, and other trace heavy metals.

Table AIV-1: Typical Properties of Uranium Mill Tailings

This table displays the chemical and radiological properties of the three classifications of uranium mill tailings (sand, slime, and liquid). Table was adapted from U.S. NRC 1980 and found in U.S. EPA 2006

Tailings Component	Particle Size (μm)	Chemical Composition	Radioactivity Characteristics
Sands	75 to 500	SiO_2 with <1 wt% complex silicates of Al, Fe, Mg, Ca, Na, K, Se, Mn, Ni, Mo, Zn, U, and V; also metallic oxides	0.004 to 0.01 wt % $U_3O_8{}^a$ Acid Leaching: 26-100 pCi ^{226}Ra/g; 70 to 600 pCi ^{230}Th/g
Slimes	45 to 75	Small amounts of SiO_2, but mostly very complex clay-like silicates of Na, Ca, Mn, Mg, Al, and Fe; also metallic oxides	U_3O_8 and ^{226}Ra are almost twice the concentration present in the sands Acid leaching:^{b} 150 to 400 pCi ^{226}Ra/g; 70 to 600 pCi ^{230}Th/g
Liquids	c	Acid leaching: pH 1.2 to 2.0; Na^+,NH_4^+, SO_4^2, Cl, and PO_4^3; dissolved solids up to 1 wt % Alkaline leaching: pH 10 to 10.5; CO_3^2 and HCO_3; dissolved solids 10 wt %	Acid leaching: 0.001 to 0.01% U; 20 to 7,500 pCi ^{226}Ra/L; 2,000 to 22,000 pCi; ^{230}Th/L Alkaline leaching: 200 pCi ^{226}Ra/L; essentially no ^{230}Th (insoluble)

a U_3O_8 content is higher for acid leaching than for alkaline leaching

b Separate analyses of sands and slimes from alkaline leaching process are not available. However, total ^{226}Ra and ^{230}Th contents of up to 600 pCi/g (of each) have been reported for the combined sands and slimes.

c Particle size does not apply. Up to 70 % vol. of the liquid may be recycled. Recycle potential is greater in the alkaline process.

The five on-site environmental pathways through which these tailings impoundments pose a risk are represented schematically in Figure AVI-3. In addition to the on-site scenarios, tailings have also been taken off-site and used as an inexpensive building material by some local populations. Each of these hazard pathways is listed below and the associated risks are discussed later.

(i)   The release of gaseous radon-222 to the atmosphere and subsequent inhalation

(ii)   Possible dust loading of contaminants from the impoundment due to natural wind conditions

(iii)   The localized effect of direct external gamma radiation exposure from the tailings impoundment

(iv)   Ground seepage and subsequent contamination of local aquifers, which has the potential to affect the water supply

(v)   Dam failure due to erosion or natural disasters (flood, earthquake, etc.)

(vi)   Improper use of tailings as a building material

All six of these hazard scenarios can apply to the general public and, with the exception of building materials, to the plant workers themselves. In addition, plant workers have added risks associated with accidents that may occur within the mill. The additional issues associated with workers are discussed in a separate section.

Figure AIV-3: On-Site Accident and Risk Scenarios Associated with Uranium Mill Tailings
This Figure shows a visual depiction of the possible environmental and health related pathways of concern

Source: http://www.wise-uranium.org/uwai.html
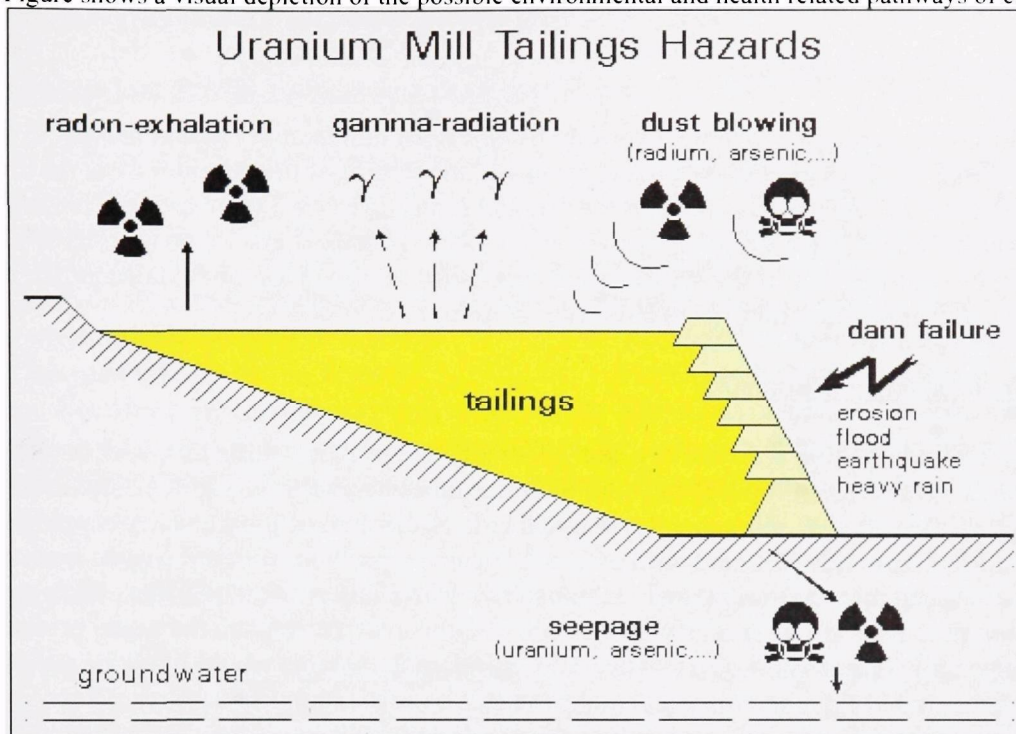
(i)   Gaseous Radon-222 Inhalation

Radon-222 is an inert radioactive gas that can readily diffuse to the surface of a tailings impoundment where it would be released to the atmosphere. The main hazard of radon inhalation is the damage to the lung from four of its shorter-lived decay products (Po-218, Pb-214, Bi-214, and Po-214). Of particular concern are the two isotopes of polonium (Po-218 and Po-214), because they produce alpha particles, which are approximately 20 times more destructive than gamma or beta radiation. Because radon-222 has a half-life of approximately 3.8 days, it has the opportunity travel a significant distance in the atmosphere before decaying. U.S. EPA (1983) states that the health of populations living at a distance greater than 80 km from a tailings pile might be affected. The radon concentration at the edge of a typical tailings pile is approximately 4 pCi/l (WISE 2004). Using the methodology outlined in Chapter 1 of this report, a year-long exposure under these conditions would correspond to a lifetime risk of lung cancer of 1.1×10^{-2}.

(ii)   Inhalation of Particles from Dust Loading

Dust loading occurs when wind blows over a dried portion of the tailings and dust containing hazardous contaminants is suspended in the air. Dust loading typically becomes a hazard in the post-operational phase of a uranium mill, as the tailings pile begins to dry, and may be exacerbated by any de-watering treatment that is performed to minimize ground seepage [see section (iv)]. The hazards associated with dust loading are dependent on the weather conditions and the amount of dried material that is available for suspension. It has been estimated that a person would have to inhale 2 grams of uranium mill tailings in a year to reach the annual dose limit for the general public (100

mrem). Assuming a continuous exposure and a breathing rate of 0.9 m^3/hr, this would correspond to a dust loading of 0.24 mg/m^3 (WISE 2004).

(iii)   Direct Gamma Exposure

Uranium mill tailings pose an external exposure hazard from radioactivity that is present in the waste. Although milling operations generally remove about 90% of the uranium from the ore, the remaining waste can contain up to 86% of the original radioactivity which is mostly composed of uranium decay products such as radium and thorium. Worst-case external exposures have been estimated to be 0.41 mrem/h, if the subject were standing directly on top of the tailings; for a continuous yearly exposure, this yields a dose of 3.6 rem.

(iv)   Groundwater Contamination

Groundwater contamination is so heavily dependent on site-specific parameters, such as the chemical characteristics of the waste products and soil, the location of neighboring aquifers, and the hydrology and geology of the site, that any general numerical risk assessment of groundwater contamination is of limited utility. Groundwater contamination can become a problem if liquid wastes from tailings impoundments seep into the ground and are transferred into shallow local aquifers. Mills employing acid leaching processes are of special concern, because this method renders the waste products more soluble than an alkaline leach process. The radiological contaminants would likely be pulled out of the seepage water into the immediate soil and so do not have the mobility to move offsite into neighboring aquifers. However, water-soluble non-radiological hazards may be problematic, including molybdenum, selenium, chlorine, sulfate, nitrate, arsenic, lead, and vanadium. An NRC report (1980) concluded that 95% of any possible groundwater contamination would occur while the site was in operation. Also, seepage should be expected unless the tailings pile was built on an artificial liner or impermeable natural clay formations. Besides lining tailings impoundments, milling waste is sometimes dewatered before disposal to reduce the risk of groundwater contamination. Dewatering, however, causes an increase in the rate of radon gas emissions (increase by a factor of 3.4 when comparing wet versus dry tailings) and also makes the pile more susceptible to wind-driven dust loading. An example of dewatering occurs at the White Mesa Mill, where the dry tailings are stored in an approved below-grade disposal cell. This disposal cell is covered with the excavated earth to mitigate the effects of radon emission and dust loading (Hochstein 2003).

Current controls exist as a result of the passage of UMTRCA to eliminate this hazard from existing and future licensed operations, as well as a certain number of previously closed and abandoned mills (see Volume I, Appendix VI for more background information). The EPA has been taking steps to work with the Navajo Nation to identify buildings constructed with uranium mine and mill wastes to assess their radiation risks, and conduct removal or other appropriate actions if necessary.

(v)   Tailings Pile Dam Failure

The least predictable risk associated with conventional uranium milling operations is the failure of a tailings dam. A dam might fail because of poor design, natural erosion of the dam, or natural disasters such as flooding, heavy snow fall, tornados, or earthquakes. In the United States, notable dam failures include the 1977 spill in Grants, New Mexico (50,000 tons of sludge and several million liters of contaminated water), and the 1979 spill in Church Rock, New Mexico (1000 tons of sludge and 400 million liters of contaminated water). The second of these noted spill events, Church Rock,

is the most notorious. It heavily contaminated the Rio Puerco river and shallow aquifers located near the river, which were used by the Navajo Nation as both an agricultural and domestic water source. As of 2003, the Navajo are still unable to use this water (Ali 2003).

(vi)   Improper Use of Mill Tailings as a Building Material

As stated in Chapter 4 of the main report, the risk of radiological exposure to the general public is not only from the tailing piles themselves, but also the improper use of mill tailings as building materials. The sandy properties of mill tailings and their availability in certain economically depressed areas make their inclusion in concrete and use as a building material possible. This has occurred when tailings piles have been abandoned without having been properly closed, or when piles of tailings have fallen from trucks along rural highways. Though the problem has been documented in Grand Junction, Colorado (Elmer 2005), Monticello, Utah (EPA 1989), on the Navajo reservation in New Mexico, and elsewhere, its current pervasiveness remains unknown. Tables 4.1 and 4.2 of the main report present annual dose values based on a few sample activity concentrations within a Navajo hogan. See Chapter 4 of the main report for more in-depth discussion and analysis of the improper use of tailings.

Summary of Modeled Risks to the Public

In a study by the Nuclear Regulatory Commission, a generalized case was modeled in which it was assumed that a "low level" of environmental controls were in place. This report concluded that if the mills in place during the time of the study (by 1980 there were 16 mills producing approximately 43,900 megatons of ore annually) were in full operation through the year 2000, it would result in approximately 610 premature deaths in North America through the year 2100 and 6,000 premature deaths through the year 3000. This model was based on a low level of environmental control, and did not take into account mitigating factors, such as covering the tailings to reduce the atmospheric release of the radon. The estimated 15-year committed dose to the public is shown in Table AVI-3, at the end of the document, which also includes an estimate of the risk as a percentage of the risk from normal background radiation exposure. For example, an individual near by a cluster of mills would accrue a 15-year committed dose of 340 mrem to the lung (an effective dose equivalent* of 41 mrem), and would represent an increase of 38% above the normal risk from background exposure (U.S. NRC 1980).

These risk estimates for fatal cancer have since been updated in U.S EPA (1983) and the results are shown in Table AVI-2. This study estimated the individual risk of cancer for a 15-year exposure to an individual at distances of 1,000-20,000 meters from the mill. The model also takes into account whether the mill was in an operational or post-operational phase. For each phase of operation, the individual 15-year risk is given as an average and a maximum value. The maximum value represents the individual who is downwind of the mill, while the average value represents the average of all wind directions (U.S. EPA 1983).

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* Effective dose equivalent based on the tissue weighting factors of ICRP-26

Table AIV-2: Results of the 1983 EPA Study[a] – Estimated 15-Year Risk of Fatal Cancer by Region and Phase of Operation

Distance (meters)	Total Risk (Operational Phase)		Total Risk (Post-Operational Phase)	
	Average	Maximum	Average	Maximum
1000	1.12E-03	1.97E-03	1.82E-03	3.18E-03
2000	3.39E-04	6.78E-04	5.51E-04	1.12E-03
3000	1.76E-04	3.60E-04	2.76E-04	5.72E-04
4000	1.17E-04	2.33E-04	1.89E-04	3.82E-04
5000	8.48E-05	1.74E-04	1.38E-04	2.76E-04
10000	3.18E-05	6.57E-05	5.09E-05	1.04E-04
20000	1.40E-05	2.76E-05	2.33E-05	4.45E-05

[a] Risk estimates are derived U.S. EPA 1983 Tables 6-1 and 6-2

Some studies of risks to human health from uranium mills have been conducted in the last several years (Boice et al 2007; Pinkerton et al 2004; Boice et al 2003). The authors reported no increases in mortality to some statistically significant increases in mortality for some diseases. However, all three studies share problems of limited size and control for confounding factors, such as lack of smoking data, specific exposure data, and population migration. Thus, the results of the studies are uninformative about the potential risks from uranium mills.

Additional Risks to Workers

Mill workers, beyond the six pathways described above, experience added risks associated with accidents inside the milling facility. The hazards due to chemical spills inside the plant exist, but may be minor relative to potential radiological accident scenarios.

At acid leaching mills, sulfuric acid is present. Though the acid is corrosive to the skin and eyes, the leaching process is carried out at atmospheric pressure, and the risk of workers coming into contact with a spray during a pipe failure is not plausible. If there were a fire coupled with the release of sulfuric acid, then the inhalation of acid aerosols and sulfur dioxide could result in severe irritation of the eyes, mucous membranes, and respiratory tract. In addition to sulfuric acid, ammonia is often added to help control the pH level during the uranium precipitation phase. It is likely that this ammonia would be under significant pressure, creating the risk of a spray, in the event of a pipe failure, that poses a risk to the skin and eyes of any nearby worker. The ammonia would also quickly evaporate, adding an inhalation hazard if the accident occurred in a poorly ventilated area.

The radiological hazards associated with milling work potentially involve the yellowcake product in a dangerous respirable form. The two most notable accident scenarios are a thickener tank failure where the yellowcake slurry is spilled to the floor and allowed to dry, or a yellowcake dryer accident. Inhalation of the yellowcake particulates is a significant inhalation hazard, because of the presence of U_3O_8 in the cake. The reader is referred to Appendix III: Risks Associated with *In Situ* Leaching [see section (ii) Radiological Hazards] for a more detailed description of operational accidents in the milling facility, specifically those involving yellowcake.

In the NRC report (U.S. NRC 1980), it was calculated that the committed annual dose to a worker at a conventional milling facility ranges from 2.0 rem to the bone up to 7.1 rem to the lung. These

annual doses would result in an effective dose equivalent of 240 mrem to the bone marrow (red) and 60 mrem to the bone surface and lung. Any exposures accrued because of accidental exposure to yellowcake would be in addition to this. This information is summarized in Table AVI-3 found at the end of the document. A study by Pinkerton et al (2004) reported mixed results in a study of a cohort of uranium mill workers, but concluded that for several limiting factors, such as small cohort size, they could not make "firm conclusions about the relation of the observed excesses in mortality."

Summary

The primary hazard associated with conventional uranium milling operations is the high level of radioactive contamination contained in the mill tailings (waste products). The decay progeny of uranium are the most significant of these radioactive contaminants, including radium and radon-222, which readily moves through the interstitial spaces of the tailing pile and is released to the atmosphere. Once inhaled, radon and its decay progeny can cause significant damage to the lung via alpha radiation. Other radiological hazards include direct gamma exposure from the tailings pile and the inhalation of any dust resuspended by wind. These hazards are typically mitigated through the use of a suitable cover over the tailing to reduce the radon released to the atmosphere and attenuate direct gamma exposure. A suitable cover can also eliminate the risks associated with the suspension of dust in the air.

Ground seepage of chemically hazardous constituents of tailings piles has been known historically to contaminate nearby aquifers. Modern milling facilities often employ a liner beneath tailings piles to prevent any ground seepage and subsequent groundwater contamination. The NRC concluded that 95% of the possible contamination would happen while the mill was operating, and that the threat was mainly from toxic elements such as arsenic, not the radioactive constituents of the pile.

As with any industrial facility, safe management practices are critical to the safe operation of uranium mills. Catastrophic accidents, such as a dam failure, have the potential to release large quantities of tailings, resulting in the contamination of local water supplies and the residential population. The improper use of mill tailings as a building material can also pose a severe radiological risk to private individuals, particularly in tribal communities. Accidents occurring within the milling facility could expose workers to chemical risks, and radiological risks from contact with or inhalation of uranium yellowcake.

Table AIV-3: Results of the 1980 NRC Model Uranium Mill Study – Committed Dose Values
From: U.S. NRC (1980)

Receptor	Dose Commitment[a] (mrem)			Risk from Mill as Percentage of Risk Due to Background (%) [b,c]
	Whole Body	**Bone**	**Lung**	
Nearby Individual[d]				
Annual 40 CFR 190 doses (excluding radon)				
1 mill	3	45	30	--
Mill cluster	4	51	36	--
Total Dose (including radon)				
1 mill	9.7	51	220	25
Mill Cluster	13	61	340	38
Average Individual[e]				
1 mill	0.061	0.50	1.6	0.19
Mill Cluster	0.66	5.8	16	1.9
Average Worker[f]				
Annual	450	2000	7100	800
Career[g]	2.1×10^4	9.3×10^4	3.3×10^5	800
Background	143	250	704	--

[a] All doses shown are total annual 15th-year dose commitments except where noted as being those covered by 40 CFR 190 limits.

[b] The range in risks due to uncertainties in health effects models extends from about one-half to two times the central value. This range does not include uncertainties in other areas (e.g. source term estimates and dose assessment models).

[c] Risk comparisons are presented for exposure received during entire mill life; that is, 15 years of exposure during operation of the mill, and 5 years of post-operation exposure while tailings are drying out, are considered. This value is greater than that from annual exposures presented because tailings dust releases increase in the period when tailings are drying.

[d] The "nearby individual" occupies a permanent residence at a reference location about 2 km downwind of the tailings pile.

[e] The "average individual" exposure is determined by dividing the total population exposure in the model region by its population total.

[f] The "average worker" exposure is determined by averaging exposures expected at the various locations in the typical mill.

[g] The career dose is based on a person who has worked 47 years in the milling industry (that is, from ages 18 to 65).

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Appendix V. List of Acronyms and Abbreviations and Glossary of Terms

List of Acronyms and Abbreviations

Ac	actinium
ac	acre
ac-ft	acre-feet
ACAA	American Coal Ash Association
AEA	Atomic Energy Act
AEC	Atomic Energy Commission
ALARA	As low as reasonably achievable
AMD	acid mine drainage
AML	abandoned mine lands
ARAR	Applicable or Relevant and Appropriate Requirement
ARD	acid rock drainage
As	arsenic
ATSDR	Agency for Toxic Substances and Disease Registry
ATV	All-terrain vehicle: A two-, three-, or four-wheeled vehicle capable of operation off paved roads.
Ba	barium
BASINS	Better Assessment Science Integrating Source and Non-point Sources (USGS computer model)
BAT	best achievable technology
Bi	bismuth
BPCT	best practicable control technology
Bq/kg	Becquerel/kilogram.
BRC	Bureau of Radiation Control
CAA	Clean Air Act
CaSO$_4$	calcium sulphate (formula for gypsum)
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Regulations
Ci	Curie(s) (unit of radioactivity, 3.7×10^{10} disintegrations per second)
cm	centimeter

COD	chemical oxygen demand
Cr	chromium
CRCPD	Conference of Radiation Control Program Directors
Cu	copper
CWA	Clean Water Act
D&D	decontamination and decommissioning
DOE	Department of Energy
DOI	Department of the Interior
dscm	dry standard cubic meter
E	used to denote exponents (3.7E+10)
EIA	Energy Information Administration (U.S. Department of Energy)
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute
$^{\circ}F$	degrees Fahrenheit
Fe	iron
$FeCl_3$	ferric chloride
FeP	ferro-phosphorus
FeS_2	pyrite
FIPR	Florida Institute of Phosphate Research
Fr	francium
ft	feet
G	gram
GIS	geographic information system
g/cm^3	gram per cubic centimeter
Gy	Gray
H	hydrogen
ha	hectare, 2.471 acres
HDS	high-density sludge
Hg	mercury
Hr	hour
ISL	in situ leaching
K	potassium

K_d	element-specific soil/water partition coefficient
Kg	kilogram
km	kilometer
L	liter
LTSP	long-term surveillance plan
μ	micro, 10^{-6}, used in combination with specific units of measurement or radiation
μg/m	microgram per meter
μg/m^3	microgram per cubic meter
μm	micrometer – one-millionth of a meter (micron)
μR/hr	microRoentgen per hour
m_	milli, 10^{-3}, used in combination with specific units of measurement or radiation
m	meter
m^2	square meter
m^{2}s	square meters per second
m^3	cubic meter
MAS/MILS	Minerals Availability System/Minerals Industry Location System (USGS database)
Mbd	million barrels per day
MCL	maximum contaminant level
MeV	Million Electron Volts
Mg	milligram
mL	milliliter
MMTs	millions of metric tons
Mn	manganese
Mo	molybdenum
MOU	memorandum of understanding
Mrem	millirem
mR/hr	milliRoentgen per hour
mSv	milliSievert
MT	metric ton(s), 1,000kg, or 2,200 lb
n	nano, 10^{-9}, used in combination with specific units of measurement or radiation

NAAQS	National Ambient Air Quality Standards
NAMLRP	Navajo Abandoned Mine Lands Reclamation Program
NARM	naturally occurring and accelerator-produced radioactive material
NAS	National Academy of Sciences
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act
NESHAP	National Emission Standards for Hazardous Air Pollutants
NFS	National Forest Service
NNEPA	Navajo Nation Environmental Protection Agency
NORM	naturally occurring radioactive material
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NPS	National Park Service
NRC	Nuclear Regulatory Commission
NSPS	New Source Performance Standards
O_2	oxygen
ORIA	Office of Radiation and Indoor Air (U.S. EPA)
OSHA	Occupational Safety and Health Administration
OSM	Office of Surface Mining
p	pico, 10^{-12}, used in combination with specific units of measurement or radiation
Pa	proactinium
Pb	lead
pCi/g	picocurie per gram
pCi/L	picocurie per liter
pCi/m^2/s	picocurie per meter squared per second
pH	negative log of hydrogen ion concentration (measure of acidity and alkalinity)
Po	polonium
ppb	parts per billion, 10^{-9}
ppm	parts per million, 10^{-6}
Pu	plutonium
PRGs	preliminary remediation goals

QA/QC	quality assurance/quality control
R	Roentgen
r^2	correlation coefficient
Ra	radium
RCRA	Resource Conservation and Recovery Act
Rem	Roentgen equivalent in man
RESRAD	computer model to evaluate risks/doses from RESidual RADiation materials
ROD	record of decision
s	second
SAB/RAC	Science Advisory Board/Radiation Advisory Committee (with U.S. EPA)
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
Se	selenium
SEO	State Engineer's Office
SIP	State Implementation Plans
SMCRA	Surface Mining Control and Reclamation Act
Sr	strontium
SSL	soil screening level, in pCi/g
STE	treatment, storage, and disposal
Sv	Sievert
TDS	total dissolved solids
TENORM	technologically enhanced, naturally occurring radioactive material
Th	thorium
Tl	thallium
TNRCC	Texas Natural Resources Conservation Commission (now Texas Commission on Environmental Quality)
tpd	tons per day
TRC	Texas Railroad Commission
TSS	total suspended solids
TWC	Texas Water Commission
U	uranium

U_3O_8	oxide of uranium
UIC	underground injection control
ULD	uranium location database
UMTRA	Uranium Mill Tailings Remedial Action program (U.S. DOE)
UMTRCA	Uranium Mill Tailings Radiation Control Act of 1978
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UO_2	uranium dioxide
UO_2SO_4	uranium sulfate
$USiO_4$	coffinite (a uranium ore)
U.S. ACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTi_2O_6	brannerite (a uranium ore)
WL	working level
y^3	cubic yard(s)

Glossary of Terms

Adits	Horizontal or nearly horizontal passages driven from the surface for the working or dewatering of a mine. If driven through a hill or mountain to the surface on the other side, it would be a tunnel.
AIRDOS	An EPA computer program for calculating doses and risks from airborne emissions of radioactive materials.
ALARA	Acronym for As Low As (is) Reasonably Achievable: A basic concept of radiation protection which specifies that exposure to ionizing radiation and releases of radioactive materials should be managed to reduce collective doses as far below regulatory limits as is reasonably achievable considering economic, technological, and societal factors, among others.
Alpha Particle	A positively charged helium nucleus (two protons and two neutrons) emitted by some radioactive materials undergoing radioactive decay.
Applicable or Relevant and Appropriate Requirement (ARAR)	Under CERCLA, cleanups must follow two kinds of requirements: • Applicable requirements meaning those that directly apply to the situation, or • Relevant or appropriate requirements meaning those that apply to contaminants that are present at the site or apply to contaminated medium, such as water, at the site. For example, the standards for cleaning up uranium and thorium processing facility sites are frequently considered "relevant and appropriate" for radiologically contaminated sites that did not conduct such processing. • ARARs can be federal, state, or local requirements.
Aquifer	An underground geological formation or group of formations containing water. Source of groundwater for wells and springs.
Average Exposed Individual	The average individual in the regional population within a 50-mile (80-km) radius of the model mine.
Background Radiation	Is radiation from cosmic sources, naturally occurring radioactive material, including radon (except as a decay product of source or special nuclear material), and global fallout as it exists in the environment from the testing of nuclear explosive devices or from nuclear accidents like Chernobyl.
Beneficiation	The initial attempt at liberating and concentrating a valuable mineral from extracted ore. This is typically performed by employing various crushing, grinding, and froth flotation techniques. The remaining (beneficiated) material is often physically and chemically similar to the material (ore or mineral) that entered the operation, except that particle size reduction has often occurred.

Berm	A horizontal shelf or ledge built into the embankment or sloping wall of an open pit, quarry, or ground surface to break the continuity of an otherwise long slope and to strengthen its stability or to catch and arrest slide material.
Beta Particle	An electron emitted from an atom's nucleus during radioactive decay.
Bioremediation	The use of biological agents, such as bacteria or plants, to remove or neutralize contaminants, as in polluted soil or water.
Brannerite	A radioactive, uranium-bearing mineral, $(U,Ca,Y,Ce)(Ti,Fe)_2O_6$.
Breccia	A coarse-grained clastic rock, composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix. Breccia may originate as a result of talus accumulation, explosive igneous processes, collapse of rock material, or faulting.
Byproduct Materials	Tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes. Underground ore bodies depleted by such solution extraction operations do not constitute byproduct materials within this definition.
Carbonates	A sediment or sedimentary rock formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron; e.g., limestone and dolomite.
Cleanup	Actions taken to deal with a release or threatened release of hazardous substances that could affect public health or the environment. The term is often used broadly to describe various Superfund response actions or phases of remedial responses, such as remedial investigation/feasibility study. Cleanup is sometimes used interchangeably with the terms remedial action, response action, or corrective action.
Coffinite	A naturally occurring uranium mineral, $U(SiO_4)_{1-x}(OH)_{4x}$.
Consolidated materials	In geology, any or all of the processes whereby loose, soft, or liquid earth become firm and coherent, either cemented or non-cemented together.
Contamination	The presence of residual radioactivity, heavy metals, or other pollutants in excess of levels that are acceptable for release of a site or facility for unrestricted use.
Conventional Mining	Mining which uses either mechanical open-pit surface mining methods, underground mining methods, or a combination of both, to extract ore from the ground. This is opposed to unconventional or solution mining methods.
Core Sample	A soil, rock, or sediment sample taken by core drilling.

Curie (Ci)	The customary unit of radioactivity. One curie (Ci) is equal to 37 billion disintegrations per second (3.7×10^{10} dps = 3.7×10^{10} Bq), which is approximately equal to the decay rate of one gram of Ra-226. Fractions of a curie, e.g. picocurie (pCi) or 10^{-12} Ci and microcurie (μCi) or 10^{-6} Ci, are levels typically encountered in radiation measurements of NORM or TENORM.
Decline	A downward ramp.
Decommissioning	The process of removing a facility or site from operation, followed by decontamination, and license termination (or termination of authorization for operation) if appropriate. The objective of decommissioning is to reduce the residual radioactivity or contaminants in structures, materials, soils, groundwater, and other media at the site so that the concentration of each radionuclide contaminant that contributes to residual radioactivity is within the cleanup limits established for the site.
Distribution Coefficient	(Soil/Water Distribution Coefficient, K_d) The ratio of the concentration of a substance in soil or rock (g^{-1}) to the concentration of that substance in water (($mL)^{-1}$). It has units of volume/mass, e.g., mL/g.
Dose	A general term used to refer to the amount of energy absorbed by a material exposed to radiation.
Drill Cuttings	The particles of rock produced in a borehole or drill hole by the abrasive or percussive action of a drill bit; erosive effect of the circulating liquid; or cavings from the borehole. At some mines and operations sites, cores of rock from a well or borehole may be left behind as waste, referred to in this report as drill cuttings for convenience.
Drilling Wastes	Wastes associated with a drillhole operation at a mine or extraction facility that are not considered cuttings or cores. May include drill muds or other drilling fluids, sludges, or evaporation products collected in excavated pits from wastewater produced during drilling.
Ecosystem	A specialized community, including all the component organisms, that forms an interacting system; for example, a marsh, a shoreline, or a forest; encompassing air, water, and land or habitats supporting plant and animal life.
Effective Porosity	The volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.
Electrodialysis	A means of extracting one or more dissolved materials from a liquid mixture, the process is dialysis assisted by the application of an electric potential across a semi-permeable membrane.
Elution	The process of removing an economic substance (e.g., uranium) from an ion exchange filter or resin.

Evaporative Ponds	Areas where mine water or other produced water is placed and dried by evaporation, leaving a residue of solids or sludges.
Evaporite	An inorganic chemical sediment that precipitates when the salty water in which it had dissolved evaporates.
Excavated Wall	A wall of mineral ore that has been exposed by mining over a considerable width at one time.
Exposure Pathway	The route by which radioactivity travels through the environment to eventually cause radiation exposure to a person or group (e.g., air or water). Also, the route by which a member of the public is exposed (e.g., ingestion, inhalation).
Exposure Scenarios	A set of conditions used in calculating exposure to a toxic material. Typical parameters in an exposure scenario include: duration of exposure, distance from the source of the material, breathing rate, and nature of any liquid or food consumption. Exposure scenarios are often named for a set of conditions for a particular activity, such as residential scenario, occupational scenario, or recreational scenario.
External Radiation	Radiation from a source outside the body.
Extraction Facility	An industrial complex and land on which are located buildings, wells and pipelines, mechanical and chemical equipment, storage and transportation equipment licensed by the Nuclear Regulatory Commission or its Agreement States for the purposes of extracting uranium (source material) in accordance with the Atomic Energy Act.
Extraction Process	A process used to extract uranium from ore, either by milling and chemically treating the ore, or using chemical solutions to treat underground ore (in situ leaching), or by treating mined and crushed ore on the surface (heap leaching). These processes are licensed activities by the Nuclear Regulatory Commission or its Agreement States in accordance with the Atomic Energy Act.
Gamma Radiation	Penetrating high-energy, short-wavelength electromagnetic radiation (similar to X-rays) emitted during radioactive decay. Gamma rays are very penetrating and require dense materials (such as lead or steel) for shielding.
Gangue	The valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration.
Garnet	A group of silicate minerals found in igneous rocks, usually red in color, used as a semi-precious stone in crystalline form, or ground into smaller particles and used for abrasives such as in sandpaper coating.
Geographic Information System (GIS)	A computer system capable of integrating, storing, editing, analyzing, sharing, and Information displaying geographically referenced information.

Graded screening approach	Uses three tiers becoming progressively more rigorous and detailed: a scoping assessment, a screening ERA, and a more detailed ERA that uses site-specific information.
Half-life ($t_{1/2}$)	The time required for one-half of the atoms of a particular radionuclide present to disintegrate.
Heap leaching	A method of extraction by which mineral bearing ores are leached on the ground surface from weathered low-grade ore. The crushed material is laid on a slightly sloping, impervious pad and uniformly leached by the percolation of leach liquor trickling through the beds by gravity to ponds. The metals are recovered by conventional methods from the solution.
Hogan	The typical dwelling of the Navajo Indians, built of earth walls supported by timbers.
Igneous Rock	Rock or mineral that solidified from molten or partly molten material, i.e., lava or magma. These rocks constitute one of the three main classes into which all rocks are divided: igneous, metamorphic, and sedimentary.
Ilmenite	An iron-black, opaque mineral ($FeTiO_3$) which is the principal ore of titanium.
Incline	A slanting shaft from the surface into an underground mine. Most commonly referring to an upward slope.
Infiltration rate	The velocity at which water enters into the soil. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour.
In Situ Leaching (ISL)	A method of extraction by which mineral bearing ores are leached underground by the introduction of a solvent solution, called a lixiviant, through injection wells drilled into the ore body. The process does not require the extraction of ore from the ground. The lixiviant is injected, passes through the ore body, and mobilizes the mineral, and the mineral-bearing solution is pumped to the surface from production wells. The pregnant leach solution is processed to extract the mineral sought after.
Ion Exchange	A common water-softening method often found on a large scale at water purification plants that remove some organics and radium by adding calcium oxide or calcium hydroxide to increase the pH to a level where the metals will precipitate out.
Lab Waste	Wastes of any kind generated by a laboratory, usually on-site, analyzing rock, sediment, water, or other samples obtained at the mine or extraction facility, or its vicinity.
Leachate	A solution obtained by leaching; e.g., water that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution.
Leach Liquor	Lixiviant which contains minerals dissolved from host rocks.

Leuxocene	General term for a fine-grained, opaque, whitish alteration (weathering) product of ilmenite in mineral form.
Lithologic	Character of a rock described in terms of its structure, color, mineral composition, grain size, and arrangement of its component parts; all those visible features that in the aggregate impart individuality to the rock. Lithology is the basis of correlation in coal mines and commonly is reliable over a distance of a few miles.
Lixiviant	A liquid medium that selectively extracts the desired metal from the ore or material to be leached rapidly and completely, and from which the desired metal can then be recovered in a concentrated form.
Longwall	A method of mining flat-bedded deposits, in which the working face is mined.
Million ElectronVolts (MeV)	A unit of energy used for photons and particles emitted in nuclear and atomic decay processes.
Mill Tailings	Residue of raw material or waste separated out during the processing of uranium mineral ores. Byproduct material as defined in accordance with Sec. 11e.(2) of the AEA.
Mine Footprint	The areal extent of land physically disrupted by a mine operation.
Mineral Sands	Eroded and generally unconsolidated sedimentary particles of rock minerals of sand size which have accumulated in a geologic deposit, and may be exploited or concentrated for economic purposes.
Mining	Mining is the mechanical process by which mineral ores are extracted from the earth.
NORM	Naturally Occurring Radioactive Materials. 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.
Ore	The naturally occurring material from which a mineral or minerals of economic value can be extracted profitably or to satisfy social or political objectives. The term is generally but not always used to refer to metalliferous material, and is often modified by the names of the valuable constituent; e.g., iron ore; ore mineral.
Overburden	Designates material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials or ores, especially those deposits that are mined from the surface by open cuts or open-pit methods.

Permeable Reactive Barrier	An emplacement of reactive materials in the subsurface designed to intercept a contaminant plume, provide a preferential flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals at points of compliance.
Picocurie	A unit of the rate of radioactive decay. One picocurie is 10^{-12} curies or 0.037 disintegrations per second or 0.037 Becquerels.
Pillar	A column of ore left to support the overlying strata or hanging wall in a mine, generally resulting in a "room and pillar" array. Pillars are normally left permanently to support the surface or to keep old workings water tight.
Pit Lake	A lake which has formed by accumulation of water in an open-pit mine excavation.
Pit Lake Water	Water which has filled an open-pit mine excavation, usually derived as water underground workings of the mine.
Preliminary Remediation Goals (PRGs)	Risk-based concentrations, derived from standardized equations similar to those found in the Soil Screening Guidance for Radionuclides (U.S. EPA 2000a). PRGs are intended to be used as initial guidelines, and not necessarily as final cleanup levels. An Internet-based PRG calculator and tables of default values for radionuclides can be found at http://epa-prgs.ornl.gov/radionuclides.
Process ore	Treating the ore, or using chemical solutions to treat underground ore (*in situ* leaching), or by treating mined and crushed ore on surface (heap leaching). These processes are licensed activities by the Nuclear Regulatory Commission or its Agreement States in accordance with the Atomic Energy Act.
Protore	Mineral-bearing rock that cannot be further processed at a profit under existing conditions, but that may become profitable with technological advances or price increases.
Pseudomorph	A mineral whose outward crystal form is that of, or which resembles another mineral species: it has developed by alteration, substitution, incrustation, or other mineral process.
Radiation or Radiological Survey	Measurements of radiation levels associated with a site together with appropriate documentation and data evaluation.
Radioactive Decay	The spontaneous transformation of an unstable atom into one or more different nuclides accompanied by either the emission of energy and/or particles from the nucleus, nuclear capture or ejection of orbital electrons, or fission. Unstable atoms decay into a more stable state, eventually reaching a form that does not decay further or has a very long half-life.

Radioactive Decay Rate	The mean number of nuclear transformations occurring in a given quantity of radioactive material per unit time. The International System (SI) unit of radioactivity is the Becquerel (Bq, 1 Bq = 1 disintegration per second). The special unit is the Curie (Ci, 1 Ci = 3.7×10^{10} disintegrations per second).
Radionuclide	An unstable nuclide that undergoes radioactive decay.
Radon-222 Emanation	The release of gaseous ^{222}Rn from the radioactive decay of ^{226}Ra.
Reclamation	Restoration of mined land to its original contour, use, or condition.
Recreational Scenario	A set of exposure conditions applicable to a person that is an occasional, not full-time, occupant who does not reside or work at the location of interest and engages in recreational activities.
Reductant or Reduction	The addition of hydrogen, removal of oxygen, or addition of electrons to an element or compound.
Refuse	Solid waste. Non-liquid, non-soluble materials ranging from municipal garbage to industrial wastes that contain complex and sometimes hazardous substances. Solid wastes also include sewage sludge, agricultural refuse, demolition wastes, mining equipment and mining residues. Technically, solid waste also refers to liquids and gases in containers.
Regulation	A rule, law, order, or direction from federal, state, or Tribal governments regulating action or conduct. Regulations concerning radionuclides in the environment in the United States are shared by EPA, NRC, DOE, and state and Tribal governments.
Rem	Radiation Equivalent in Man. The special unit of dose equivalent. The corresponding International System (SI) unit is Sievert (Sv): 1 Sv = 100 rem.
Remediation	Cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a Superfund site, or uranium mine or extraction facility, including those included under the Uranium Mill Tailings Radiation Control Act (UMTRCA).
Removal	The cleanup or removal of released hazardous substances, or pollutants or contaminants which may present an imminent and substantial danger; such actions as may be necessary taken in the event of the threat of release of hazardous substances into the environment; such actions as may be necessary to monitor, assess, and evaluate the threat of release of hazardous substances; the removal and disposal of material, or the taking of other such actions as may be necessary to prevent, minimize, or mitigate damage to the public health or welfare or the environment.

RESRAD	A computer program developed that is used for calculating radiation doses and risks from RESidual RADioactivity in or on soil.
RESRAD- BUILD	A computer program that is used for calculating radiation doses and risks from radioactive materials in or on buildings and other structures.
Retardation	In groundwater, the slower movement of a solute than the velocity of the fluid due to absorption, adsorption, and ion exchange with the soil matrix.
Retardation Factor/Coefficient	A measure of the capability of adsorption within the porous media to impede the movement of a particular radionuclide being carried by the fluid.
Retreat Mining	A system of removing underground pillars for their ore from a room and pillar mine operation. The mined room collapses once the pillar is removed; the operation retreats from the excavated boundary toward the shaft or mine mouth.
Rill	A small channel, as one formed by erosion.
Riparian Animal	An animal that lives both on land and in water, e.g., a muskrat.
Risk	The probability of injury, disease, or death under specific circumstances. Risk can be expressed as a value that ranges from zero (no injury or harm will occur) to one hundred percent (harm or injury will definitely occur). Risk-based standards limit the risk that releasing a contaminant to the environment may pose, rather than limiting the quantity that may be released.

• Absolute risk, the excess risk attributed to irradiation and usually expressed as the numeric difference between irradiated and non-irradiated populations (e.g., 1 case of cancer per million people irradiated annually for each rad). Absolute risk may be given on an annual basis or lifetime basis.

• Relative risk, the ratio between the number of cancer cases in the irradiated population to the number of cases expected in the unexposed population. A relative risk of 1.1 indicates a 10 percent increase in cancer due to radiation, compared to the "normal" incidence. |
Risk Assessment	Qualitative and quantitative evaluation of the risk posed to human health and/or the environment by the actual or potential presence and/or use of specific pollutants.
Room and Pillar	A conventional method of underground mining in which natural pillars are left and unmined for support between the mined rooms.
Rutile	A usually reddish-brown mineral (TiO_2) that is an ore of titanium.

Saturated Zone	A subsurface zone of soil or rock in which all the pore spaces are filled with water under pressure greater than that of the atmosphere. This zone is separated from the zone of aeration (above) by the water table.
Saturation Ratio	The fraction of the interstitial spaces between soil grains that is filled with water.
Scanning	An evaluation technique performed by moving a detection device over a surface at a specified rate to create visual images of minute particles.
Scenario	A set of conditions that describe the situation of a person's exposure to a pollutant. These conditions typically include source-to-receptor distance speed, and distance above the surface to detect radiation. It also includes duration of exposure, exposure pathways, food consumption, and air and water intake. Scenarios are commonly named for the person or activity being assessed, e.g., resident farmer scenario, recreational scenario, transportation scenario, residential scenario, and worker scenario.
Secular Equilibrium	A state of parent-daughter equilibrium that is achieved when the half-life of the parent radionuclide is much longer than the half-life of the radionuclide decay product. In this case, if the two are not separated, the decay product will eventually decay at the same rate at which it is being produced. At this point, both parent and daughter will decay at the same rate until the parent is essentially exhausted.
Sievert (Sv)	The special name for the International System (SI) unit of dose equivalent. 1 Sv = 100 rem = 1 Joule per kilogram.
Site	Any mine or extraction facility installation, or discrete, physically separate parcel of land or lands disturbed by mining or uranium extraction, or any building or structure or portion thereof.
Soils	All unconsolidated materials above bedrock.
Soil Screening Guidance (SSG)	A tool developed by EPA to help standardize and accelerate the evaluation and cleanup of contaminated soils at sites on the National Priorities List (NPL).
Solution Process	A method of extracting sought-after underground elements or minerals from in-place ore, or elements or minerals from ore previously mined and crushed. This is accomplished through the use of fluids that dissolve the mineral from the rock, putting it into liquid solution which is then processed or evaporated to obtain the desired element or mineral.
Solvent Extraction	A process for extracting a mineral or element (e.g., uranium) from ore by soaking rock with a (solvent) that dissolves the target element from the rock and putting it into liquid solution. The liquid is then processed or evaporated to obtain the desired element.

Source Materials	Uranium or thorium, or any combination thereof, in any physical or chemical form or ores that contain by weight one-twentieth of one percent (0.05%) or more of (1) uranium, (2) thorium or (3) any combination thereof. Source material does not include special nuclear material.
Special Nuclear Material	Plutonium, U^{233}, and uranium enriched in U^{235}, material capable of undergoing a fission reaction.
Stewardship	Institutional controls (private or public ownership or governmental) which may be put in place to ensure that a specific site meets its closure goals. Institutional controls can be either active, involving some form of continuous or intermittent human activity to maintain the condition of the site, or passive, which do not require human intervention and have an amount of redundancy built into them to deter or prevent disturbance of the closed site.
Stope	An excavation from which ore has been removed in a series of steps. Usually applies to mining of ore from steeply inclined or vertical veins.
Superfund Risk Criteria	The incremental cancer risk level of 10^{-6} is usually the baseline level of risk that is acceptable and 10^{-4} is typically at the highest end of the range of acceptability.
Survey	A systematic evaluation and documentation of radiological measurements with a correctly calibrated instrument or instruments that meet the sensitivity required by the objective of the evaluation.
Survey Plan	A plan for determining the radiological and other characteristics of a site.
TENORM	Acronym for Technically Enhanced Naturally Occurring Radioactive Material. Natural radioactive materials have been concentrated or exposed to the accessible environment as a result of human activities, such as manufacturing, mineral extraction, or water processing.
Transport Time	The time interval it takes for a contaminant to move through groundwater from a source to a potential receptor.
Unconsolidated Rocks	Rocks consisting of loosely coherent or uncemented particles, whether occurring at the surface or at depth.
Underflow	Flowing bottom waters containing dissolved or suspended solids.
Underground Injection	The method by which fluids are placed under pressure in a well such that the fluid enters an underground rock formation. A means by which ISL wells inject lixiviant to dissolve uranium from underground ore bodies.
Unsaturated Zone	The zone in which the pore openings of the functional permeable rocks are not (except temporarily) filled with water under hydrostatic pressure; the interstices are either not filled with water or are filled with water that is held by capillarity.

Uprate	The process of increasing the maximum power level at which a commercial nuclear power plant may operate.
Uranium (Mine) Location Database (ULD)	Uranium (Mine) Location Database. An EPA database containing data on the location of uranium mines and related facilities.
Volcaniclastic	A sedimentary rock containing volcanic material without regard to its origin or environment of deposition.
Waste Rock	Rock void of uranium ore that may have been set aside as waste after removal of top-soil, overburden and uranium ore or veins. Waste rock is defined as barren or submarginal rock or ore that has been mined, but is not of sufficient value to warrant treatment and is therefore removed ahead of the milling processes.
Wastewater	The spent or used water from a mine that contains dissolved or suspended matter.
Water table	The groundwater boundary between the saturated zone and the unsaturated or vadose zone.
Working Level	A special unit of radon exposure defined as any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy. This value is approximately equal to the alpha energy released from the decay of progeny in equilibrium with 100 pCi of Ra-222. The EPA recommended residential radon limit of 4 pCi/L is approximately equivalent to 0.02 WL.
Working-Level Month (WLM)	A person exposed to one WL for 170 hours is said to have acquired an exposure of one working-level month (WLM). This 170-hour value is based on the typical number of hours underground miners worked in one month.