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.

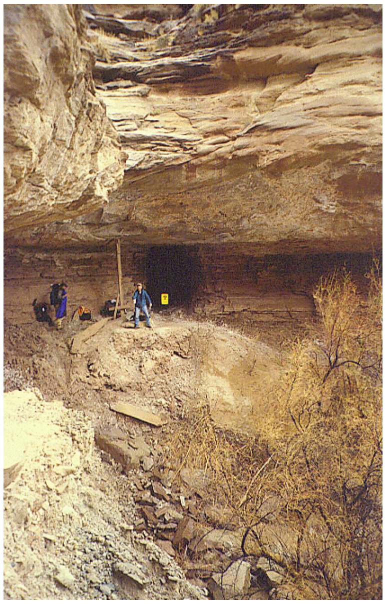
Workings vs. Waste	Mine											
	1	2	3	4	5	6	7	8	9	10	11	12
Lateral workings *in feet (meters)*	82 (25)	28 (9)	75 (23)	865 (264)	450 (137)	230 (70)	215* (66)	188 (57)	20 (6)	70 (21)	40 (12)	235 (72)
Waste *in yards^3 (meters^3)*	120 (92)	-	-	800 (612)	470 (359)			220 (168)	35 (27)	165 (126)	100 (76)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

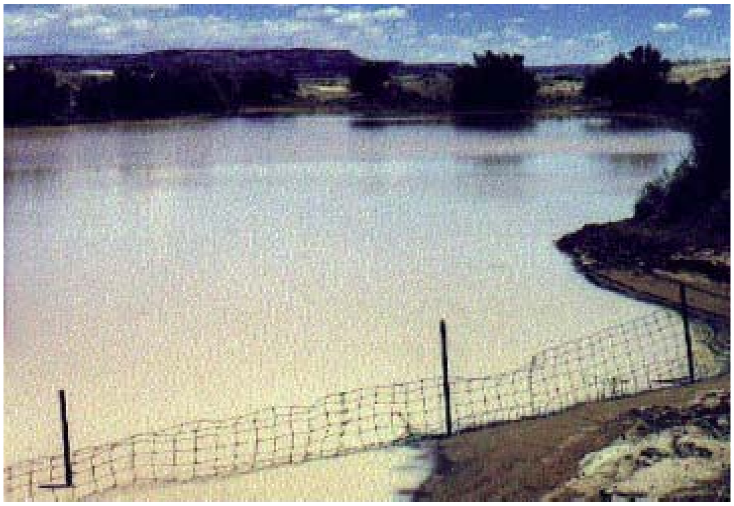
The Yazzie-312 Mine (see Appendix III) is an example of a small surface mine that had a number of both protore and overburden waste piles located adjacent to the mine pit, which had filled with water. Runoff from precipitation over a 40-year period carried fine-grained materials back into the pit. The 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.

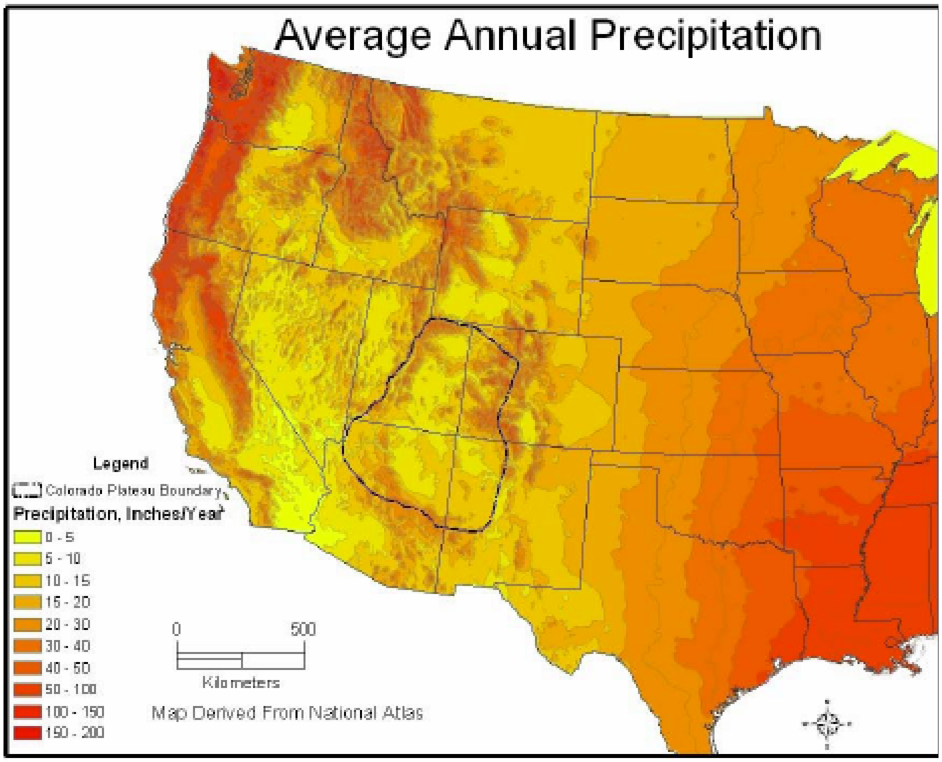
Types of mines in relation to hydrologic factors for groundwater impacts include:

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.

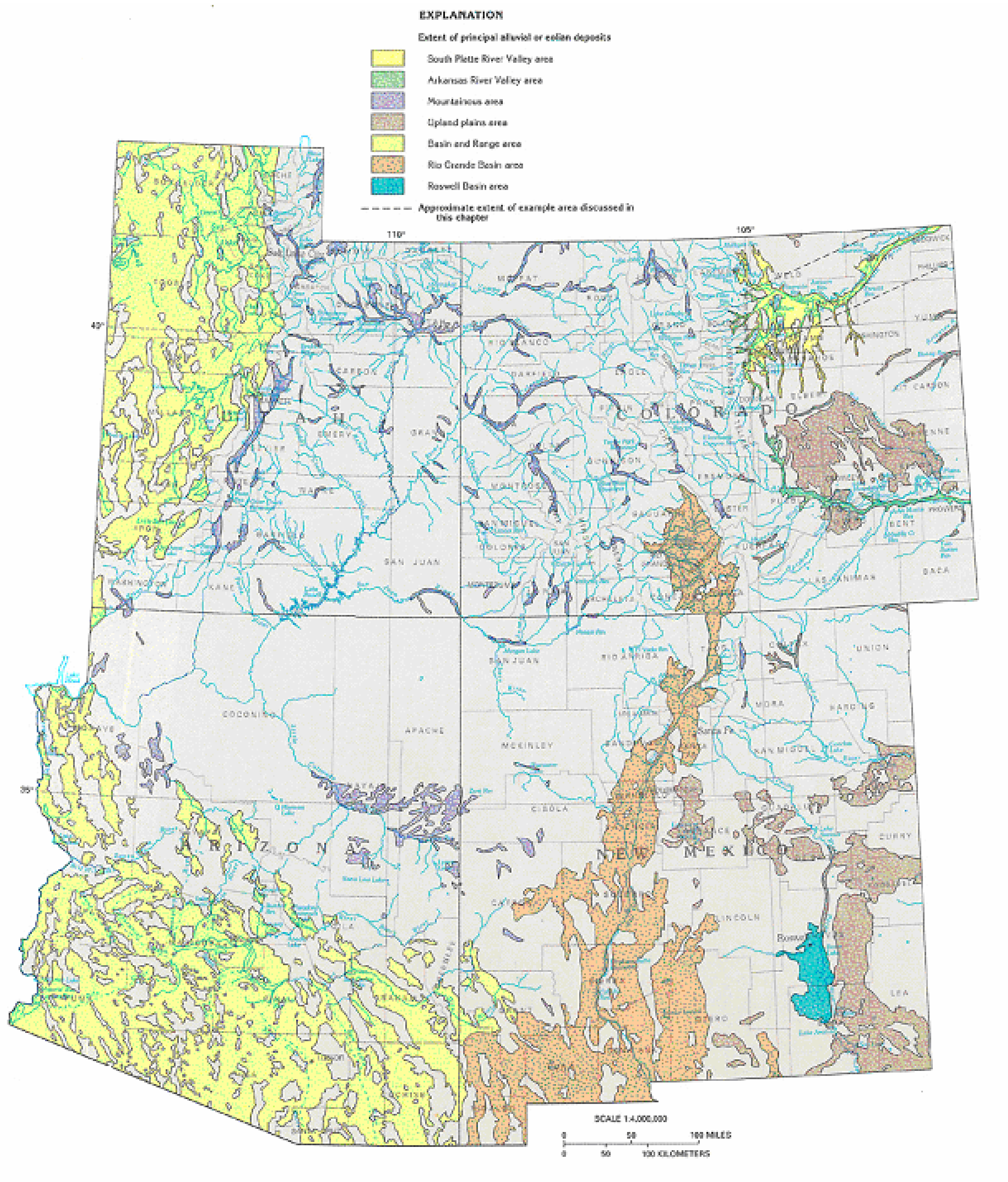
Figure 3.5. Average Annual Precipitation in the Western United States

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



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).

Elevated Radioactivity

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.

	Concentration (µg/g)														
Samples	**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)

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 (Avg. 3 samples)	61.8--121.9 (90.2)	36.8—63.4 (36.8)	1.1—9.7 (4.2)	6000--8100 (7207)	21.3—48.3 (39.1)	0.05—0.19 (0.13)	0.13—0.32 (0.25)	0.84—18.4 (6.73)	12.3—20.5 (17.7)
Waste Pile 3-Overburden range of measurements (Avg. 3 samples)	2.4—3.6 (2.9)	3.0—4.85 (3.9)	1.3—1.9 (1.5)	1020--1430 (1356)	11.8—13.8 (12.6)	0.01—0.01 (0.01)	0.27—0.93 (0.50)	0.24—0.28 (0.26)	15.2—33.5 (21.4)
All Protore and Overburden Samples Range of measurements (Avg. 12 samples)	2.4—121.9 (32.7)	3.0—63.4 (15.5)	0.7—17 (4.6)	6000--16200 (9867)	7.9—48.3 (21.8)	0.00—0.19 (0.05)	0.13—0.95 (0.47)	0.19—18.4 (1.91)	8.2—33.5 (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.