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 U_3O_8	\$0.18
Highest cost of closure, \$/lb U_3O_8	\$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.