Radioactive and other environmental contamination from uranium mining and milling

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1.1 Introduction

Mining of uranium-bearing ores dates back to the Middle Ages in Central Europe, although the target metals were silver, gold, or copper. Pitchblende encountered was dumped as waste. Pitchblende was targeted only in the early twentieth century for its radium content, and small-scale mines were operated in England (Cornwall), Portugal, and the Erzgebirge (Ore Mountains), namely in Joachimsthal, now Jachimov in the Czech Republic. The interest in uranium for military and later energy uses sparked prospecting and exploration activities all over the world from the 1930s onward, which increased significantly in intensity as the nuclear arms race gained momentum. Exploration activities lessened after the 1960s, but mining continued to increase until the end of the 1980s. The end of the Cold War led to a significant drop in demand for uranium, while surplus military uranium was fed into the energy market, making only the most efficient mines with the highest ore grades commercially viable (OECD-NEA/IAEA, 2014). From the 1990s onward, many uranium mines all around the world were closed, and their legacies began to be addressed (OECD-NEA/IAEA, 1999). With production (mainly for military use) being the paradigm, environmental impacts and long-term safety at the sites were largely neglected. This resulted in considerable environmental legacies, not only in former Eastern Bloc countries, but also, for example, in the United States (IAEA, 2000b). Some of these legacies had already been addressed in the Western countries from the 1970s onward, following the generally increasing awareness of industrial and other environmental contamination. The size of the problem in the Eastern Bloc and former Soviet Union countries became apparent only post-1990. The majority of mines were dedicated to uranium, but some mines co-mine(d) uranium together with other metals. A notable example is Olympic Dam in Australia (OECD-NEA/IAEA, 2014), which, at current uranium prices, is mainly a copper mine. Due to the depletion of high-grade deposits that are easily accessible, mining can be expected to move to lower-grade deposits, resulting in larger waste volumes, and to deeper, more difficult-to-mine deposits.

Section 1.2 of this chapter will provide an overview of the various life-cycle stages of uranium production, together with their associated residue streams and impacts. Section 1.3 discusses life-cycle management with a view to minimizing impacts. Section 1.4 discusses the existing uranium production legacies and their management. Finally, Section 1.5 provides an overview of future trends in uranium mining and processing.
1.2 The front end of the nuclear fuel cycle

1.2.1 Exploration of uranium resources and resulting waste streams

Exploration, at least in its more advanced stages, involves invasive techniques such as drilling and sampling. Drilling results in waste streams and other impacts that need to be managed adequately. Country-specific legislation for permission of drilling will cover many of these aspects. The drilling process, depending on the techniques used, results in drill chippings, mud, and cores that need to be managed to avoid environmental contamination and exposure of drilling rig personnel. A borehole may penetrate formations that not only contain uranium below a grade of interest, but also heavy metals and other elements of concern, such as arsenic. Drilling mud may contain additives (e.g., to adjust viscosity) and may also be contaminated by oils from the rig and other substances that may be harmful, when dispersed in the environment. The resulting chippings and contaminated drilling mud must be collected and, if necessary, disposed in a licensed facility. As a borehole may penetrate several water-bearing strata before reaching the target formation, it will have to be sealed carefully at each formation once the necessary samples have been taken and the borehole logging is complete. To avoid cross-contamination between different formations, the borehole may need to be cased temporarily during the drilling operation. If the borehole penetrates radionuclide-bearing formations, radiation protection measures will have to be put into place to protect the crew from direct exposure to material recovered.

Certain geophysical exploration techniques can also disturb the environment. Seismics may require the drilling of boreholes for the explosives charges, and the blast itself may disturb fauna and people. The access to land with heavy vehicles may already disturb sensitive environments and leave long-lasting traces (Figure 1.1).
Responsible exploration and mining companies today operate near-zero-disturbance exploration sites. In some cases, for example, in very sensitive environments such as the arctic permafrost, drilling installations are put onto elevated pads that isolate them from the environment (Wollenberg, 2011). All wastes are carefully collected and returned to adequate management or recycling facilities.

1.2.2 Uranium mining techniques and their waste streams and impacts

1.2.2.1 Mining techniques

The mining technique used at a given site depends on a wide variety of factors, such as the depth and extent of the mineralization, the host rock type, the grade of mineralization, but also on the socioeconomic and geographical settings (IAEA, 2000a). Open-cast mining is applied to shallower and more extended mineralizations, whereas underground mining is better suited to deeper and more compact ore bodies. In situ leaching (ISL) is gaining importance in world uranium production. Each technique results in specific waste streams and impacts.

**Open-cast mines** require large amounts of overburden to be removed and stored for later backfill. This kind of mining is generally viable only when the overburden consists of softer and less-cohesive geological materials. Due to the need to maintain safe slope angles, which depend on the consistency of the material, the footprint and land disturbance of open-cast mines is considerably larger than the mineralized zones. In consequence, the volume of the mine that needs to be dewatered is usually much larger than for a comparable deep mine (Figure 1.2) and can be of enormous extension. It may result in issues, such as water wells falling dry and acid mine drainage (AMD) when sulfide mineral–bearing strata become exposed to the atmosphere. It should be noted that these issues are not unique to uranium mining, but do occur in any type of open-cast mining. Continuous backfilling of mined-out parts will help to alleviate some of the problems: it helps to reduce the operational footprint of the mine, prevents aeration of sulfide-bearing strata, reduces the volume to be dewatered, and reduces the need for slope maintenance. To ensure geochemical compatibility, the overburden should be brought back into the pit in the same sequence as the natural geological layers (cf. Figure 1.7). The topsoil would be set aside for later use in recultivation (IAEA, 2010).

**Underground mining** results in smaller volumes to be excavated and dewatered and, hence, a smaller surface footprint of the mine (Figure 1.2). This comes at the price of higher geotechnical and workplace risks and the need to provide for ventilation against radon build-up. The layout and actual mining technique depends on the shape and location of the ore body as well as the type of host rock. For mine safety reasons, at least two shafts have to be sunk or access tunnels (inclines) dug. In practice, there may be more shafts and additional drill holes not only to provide access but also for ventilation purposes. In strong rocks, the drifts and other types of access tunnels may remain unlined, whereas in weaker rocks such “permanent” mine opening may need to be secured by linings. Liners will reduce the groundwater inflow and, hence, the amount of potentially contaminated and acidified waters to be managed. Liners
also reduce the radon burden in the mine air and thus the amount of radon emitted from ventilation shafts. Leaving mined-out areas to collapse is a practice that becomes less and less acceptable, because of potential surface effects and because it will make groundwater management more difficult after mine closure. Backfilling the mined-out areas counteracts these issues and at the same time reduces the amount of excavated material that needs to be lifted to the surface. Backfilling and sealing off mined-out areas also reduce the radon burden in the operating part of the mine and, hence, the ventilation needs.

In both cases, in an open-cast and a deep mine, the excavated ore will be brought to the surface for further processing in an industrial plant. To reduce the amount of material to be lifted, there will be some presorting underground. A refined sorting or screening will take place before the material enters the processing plant. In modern mines, much of the ore dressing is moved underground so that only the material that will be milled has to be lifted.

The efficiency of the milling process, the reagent consumption, and the commercial viability of the mill depends on the ore grade. Ore that is considered subgrade at a given moment may be subject to heap leaching (see below) or stockpiled. Such
Radioactive and other environmental contamination stockpiles may become of commercial interest if the price for yellow cake increases. In some cases, however, mines were closed before the ores stockpiled on the surface became commercially viable and as a consequence have become an environmental legacy (see Section 1.4).

**ISL**, also called *in situ* recovery or solution mining, is a technique that is considered to have a number of advantages over conventional excavation (IAEA, 1989, 1993, 2004a; USNRC, 2001, 2003) and the number of ISL mines has increased in recent years (OECD-NEA/IAEA, 2014). The main advantage is that no overburden, barren rock, and gangue need to be removed. The technique consists of drilling a number of wells that serve as injection and recovery wells (Figure 1.3). A well screen controls the inflow of groundwater into the mine area and prevents the outflow of contaminated fluids (IAEA, 2001a) by maintaining a slight drawdown cone. Although an ISL mine results in much less groundwater drawdown than conventional mines, the leaching solutions will be difficult to remove from the formation at the decommissioning stage. Well drilling results in some waste potentially contaminated (see the section on exploration) that needs to be managed. There will also be excess water to be discharged after treatment to remove any contaminants and process chemicals (IAEA, 2002d). The lixiviant can be either acidic or alkaline solutions, sometimes with oxidizing agents added. Acid ISL mines are much more frequent than alkaline ISL operations (OECD-NEA/IAEA, 2014), as commercially viable uranium mineralizations often are associated with permeable sandstones. Uranium mineralizations in carbonaceous rocks, in which acids would attack the bulk host rock, are much less frequent.
(IAEA, 2005c). ISL requires a certain permeability of the ore/host rock (which can be increased by hydraulic fracking) and accessibility of the uranium minerals within the matrix. Although ISL mines produce relatively small amounts of operational waste, their closure and remediation pose significant challenges. Contamination of aquifers, either associated with the ore or above and below the mineralized zone, has been of concern (USNRC, 2001). However, mining the mineralized zone by conventional methods is likely to have more severe overall impacts, both on site and off site. One may also note that groundwaters from ore-bearing strata may not be useable in any case for human or animal consumption, due to high natural concentrations of salinity and toxic constituents that are costly to remove.

In some mines, namely in the former GDR (Hähne & Altmann, 1993) and in the Czech Republic (Fiedler & Slezák, 1993), traditional underground mining was combined with solution mining. Here the mineralized zones were hydraulically isolated by horizontal and vertical well screens drilled from drifts underground. Internal surface areas were increased by controlled blasting. Acid was circulated through these “blocks” to leach the uranium without bringing the ore to the surface.

1.2.2.2 Mining waste types

Both deep and open-cast mines produce a considerable variety of wastes that need to be adequately managed to minimize environmental impacts and exposures.

**Open-cast mining** requires vast amounts of overburden to be removed. The amount generated depends on the geotechnical stability of the pit slopes. The less cohesive the material is, the more material has to be removed to arrive at sufficiently shallow slopes. It needs to be noted that under operational conditions, with continuous maintenance, slopes can be steeper than what is permissible after closure (see below). Depending on the size and depth of the pit, it may be possible to continuously backfill excavated material as it is being removed. Topsoil requires special attention to maintain its function as vegetation substrate. It is stored separately to be available for later recultivation of the pit area and spoil heaps, among other purposes.

Most open-cast mines have to manage large quantities of mine waters. Unlike in underground mines, controlling water inflow is possible only by backfilling, which will reduce the volume to be dewatered.

**Underground mining** results in excavated rock from sinking shafts and opening up drifts and other types of tunnels being brought to the surface. The form and consistency of the mine waste generated depends on the type of rock excavated and on the mining technique. As hoisting material to the surface is costly, modern mining aims to reduce this amount and to re-use excavated material underground. However, for a deep mine targeting a relatively small mineralized zone, this may not be feasible, as not enough underground storage space may be available.

The distinction between what is mineable ore and what is gangue depends on the available milling technology and also on the market price of yellow cake that determines the commercially viable ore grade. In consequence, subgrade ores will arise and typically are stored separately from other excavated materials, awaiting increasing market prices.
The amount of drainage water to be managed depends on the hydrogeological setting and on the permeability of the host formations. Water ingress can be reduced by casing of shafts and lining (e.g., with shotcrete) of nonproducing mine openings, as well as backfilling mined-out areas. These drainage waters come from different formations, including the mineralization itself, that will have been altered by the ingress of atmospheric oxygen. This will result in AMD so that the waters cannot be simply discharged, but need to be treated. Treatment aims at raising the pH values and at the removal of toxic or radioactive constituents as well as contamination from oils and explosive residues. The resulting treatment sludges require adequate conditioning and disposal. Some of the mine water will be reused as process water either in the mine itself or in the mill.

Radon exhalation and accumulation in the mine openings may be a workplace exposure problem. Forced ventilation will remove gaseous radionuclides (radon, thoron) from the mine, but the exhausts have to be adequately dispersed so as not to cause inadmissible exposures of the adjacent environment and its population.

A problem frequently encountered in mining areas is the unauthorized or ignorant use of mining residues. The loose material found on spoil heaps, for example, leads to its use as an aggregate in construction. When such an aggregate is used in buildings, any radionuclide content may lead to exposure to radon or even direct doses inside the buildings (USEPA, 2008; Chapter 4).

**ISL mining** will result mainly in wastes from drilling the array of injection and recovery wells. The processing of the pregnant solution will result in additional wastes that will be discussed in the section on milling. Protective wells that keep a depression cone in the water table around an ISL mine will have to discharge the excess water. As in other mines, these waters may be acidified due to sulfide mineral–bearing strata becoming exposed to the atmosphere after the lowering of the water table.

### 1.2.2.3 Mining impact pathways

Uranium mining is a practice that is controlled by both the applicable national radiation protection legislation (IAEA, 2002b) as well as mine safety and other workplace safety regulations. Impacts from industrial-type accidents are not discussed in this section, which focuses on environmental impacts. Relevant environmental impacts may arise from radionuclides (Chareyron, 2008), as well as from other constituents in mine host rocks or foreign materials introduced by the mining operation.

**Liquid effluents** in the form of drainage and leachates may contain elevated concentrations of radionuclides, heavy metals, and other toxic or noxious substances. These can include explosive residues, oils, fuels, and other compounds introduced by the mining operation. Mine effluents need to be treated to comply with discharge standards in force at the mine site (IAEA, 2002d). Treated effluents may be used to reduce water stress on vegetation over the depression cone and to augment affected surface water courses.

**AMD** generation is a major concern in the mine itself and in spoil heaps or other mine wastes, resulting in pH values as low as 2 in some cases (Nordstrom & Alpers, 1999). Although only a small fraction of the mine wastes may contain radionuclides
in relevant concentrations, there may be other metals and minerals of concern. AMD results from the percolation of oxygenated surface waters through geological materials underground or in wastes that contain sulfidic minerals, such as pyrite. Although the acidity in itself would have an impact on aquatic life when discharged without prior neutralization, it also results in the dissolution of minerals that contain toxic or radioactive elements, including heavy metals and arsenic, for instance.

Radon and thoron in the mine air are due to the presence of uranium minerals in the ore and adjacent formations. The outgassing of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ from stockpiled subgrade ore or other uranium-bearing rocks in mine waste heaps can be an issue, in addition to emission by the mine ventilation. The impact on the surrounding environment depends on the meteorological conditions and the topographic setting. It is possible that radon-enriched air becomes trapped in valleys due to meteorological inversion; for example, a layer of cold air is overlain by warmer air, resulting in reduced circulation and exchange and, hence, dilution (Steck, Field, & Lynch, 1999). This may result in elevated doses to the local populations.

Dust is raised by the action of wind from (uncapped) mine wastes and from the walls of open pits. Significant amounts of dust may also be raised during poorly controlled blasting operations in open pits. The dispersed dust can spread contamination by radionuclides and other toxic compounds. The dust may settle on residential and agricultural areas, leading to direct exposure or exposure through ingestion, for example, from agricultural and horticultural products. Dust washed off by rain may enter surface water courses and be further dispersed. Dust may be also leached out, with the contaminants being taken up by the vegetation or eventually reaching the groundwater table.

Erosion will affect uncovered and unvegetated spoil heaps and similar disposal sites that may have little erosion resistance. During rainfall events, fine-grained material will be washed out and may eventually reach streams. The accumulating bottom sediments can be re-eroded and further dispersed downstream, taking with them any heavy metals, radionuclides, and other contaminants. Inadequately placed heaps can also be prone to direct erosion by streams. Geochemical mining signatures can be found far downstream in surface water courses that drain catchment areas with mining activities.

Geotechnical issues occur in all mines, whether deep or open-cast, including uranium mines. If the deep mining technique involves letting collapse mined-out areas, the process of collapsing can cause small local earthquakes. Subsidence can occur over collapsed areas that may result in damage to buildings and other infrastructures. A major issue is the stability of slopes within open pits and of mine waste heaps. Slumping slopes or dams can affect areas outside the licensed mine area, damaging or destroying infrastructure and buildings. Strong and/or persistent rainfall events may compromise slope stability by increasing water contents of the geological materials beyond safe levels. The same problem can arise in open-cast mines, when groundwater levels rise. Raising porewater pressures may lead to ground instability. The collapse of slopes can lead to the dispersal of contaminants.

Carbon emissions. Mining is an energy-intensive process, and a wide variety of sources contribute to greenhouse gas (GHG) emissions. In open-cast mines, the
majority of mobile machinery is powered by diesel engines running on liquid fossil fuel. Underground combustion engines in vehicles may run on liquified natural gas or may be electrically driven. Stationary machinery usually is powered by electric motors. Depending on the location of the mine, the electricity is generated locally, for example, by diesel generators, or supplied by local or regional power stations. Large mines may have dedicated power stations. The carbon balance of a uranium mine and mill (Falck, 2009) depends on the power generation technology (thermal, hydro-power) and on the fuel used (oil, gas, coal, nuclear). Recent research, for example, in the context of the i2Mine project (http://www.i2mine.eu), looks into capturing the carbon emitted from machinery underground.

1.2.3 Uranium ore milling, its waste streams, and associated impacts

1.2.3.1 Ore processing

Milling. The ore extracted from underground or open-pit mines is transported to the mill typically by wheeled vehicles. The ore is sorted according to the grade and subgrade pieces may be sent for stockpiling. The rocks are crushed and ground to a small and uniform particle size to increase the surface area for the following leaching process. Unless the host rock is carbonaceous, an acid solution is used, usually sulfuric acid. The sulfuric acid is brought in or produced on site, depending on the location and available transport options. Some sulfidic ores may not require the addition of acid. An oxidizing agent, such as peroxide, may be added to help break down certain uranium minerals. The resulting slurry is stirred in reaction tanks. After a sufficient reaction time, the slurry is transferred into a settling tank and the supernatant solution containing inter alia the uranium is removed. The remaining solids are washed to further remove dissolved uranium. They are a fine suspension of particles and will be run through thickeners to remove the water for re-use. These residual solid materials are the so-called mill tailings and are disposed of in tailings management facilities.

There are different processes for recovering the uranium from the “pregnant” leaching solution. Sodium chloride, ammonium chloride, or ammonium sulfate are used as stripping solutions, or a nonaqueous liquid extraction process is used. Uranium is precipitated from the highly concentrated stripping solutions by the addition of ammonia, resulting in ammonium di-uranate (“yellow cake”). The choice of stripping process depends on the types and concentrations of other (heavy) metals dissolved by the leaching, with the intention of making the process as uranium specific as possible. There are also processes using solid ion exchangers to concentrate the uranium. The concentration processes result in waste solutions from which the unwanted metals are removed by neutralization/precipitation. The precipitates are disposed of together with the tailings, while the solutions may be re-used.

The uranium di-uranate slurry is concentrated in filter presses and then dried before packaging (usually in drums) for shipping as yellow cake to the enrichment (if applicable) and fuel fabrication process.
Potential impacts from milling plants include leaking tanks and pipework, dust generation, and radon emanation. In comparison with similar mills for other types of ore, uranium mills tend to be well maintained, as at least parts of them are “controlled practices” in a radiation protection sense.

**Heap leaching.** For low-grade ores, the process described above may not be sufficiently energy and materials efficient. Such ores may be put onto so-called leaching pads, that is, shallow ponds with drainage systems beneath. Acid or alkaline leaching solutions are continuously sprinkled over the heaps of subgrade ore, collected, and then sprinkled over the ore again until a sufficiently high uranium concentration is reached. The pregnant heap-leaching solution is processed into yellow cake, as described before.

**ISL.** *In situ* leaching combines mining and milling into one continuous process. Depending on the uranium concentrations achieved, the leaching solution is processed for uranium recovery or is recirculated and a certain portion split off for processing. The uranium is removed from the pregnant circulation fluid as described above. The barren leaching solution is returned to the ISL field for re-use. The ISL technique uses a range of chemicals to enhance the solubility of uranium underground and to adjust the pH of solutions (CO₂, NaOH, NH₄, H₂SO₄, HCl, Na₂CO₃), to precipitate the uranium (BaCl₂), to adjust the redox state (H₂S, Na₂S, H₂O₂), and to regenerate ion exchange resins used to recover the uranium (NaCl). As with any industrial plant, there is the risk of pipe and tank ruptures and other kinds of spills that could have impacts on the environment or pose health and safety risks (USEPA, 2008; Appendix III).

### 1.2.3.2 Processing wastes

**Mill tailings** are the residual slurries from the wet processing and are the main wastes from conventional ore milling. They contain, inter alia, the nuclides $^{230}$Th and $^{226}$Ra, which are typically not removed by the milling process (IAEA, 2004b). They are disposed of in tailings management facilities that may also receive other waste streams, such as neutralization slurries. The different wastes may be mixed or emplaced at different locations within a tailings pond. The water content of tailings depends on the thickening process and technology. Thickening is an energy-intensive step and is usually limited as much as possible. The mode of conveyance from the mill to the disposal site is another consideration when deciding on the water content: slurries can be easily pumped, whereas paste-like tailings need to be transported by conveyer belts.

A major long-term issue is the slow settling and dewatering of the tailings due to the colloidal nature of the finely ground particles. As the natural dewatering can take years or even decades, large volumes of ponds are needed, and decant water will need to be managed over long periods of time. Dewatering can be accelerated, for instance by wick drainages, but this is done mainly in a remediation context (see below). Re-cognizing this problem, industry has moved toward the so-called paste technology, that is, further thickened tailings (Dudgeon & Waite, 1999). Further dewatering leads to a disposal technique called “dry stacking”. These tailings cannot be pumped, but have to be transported to the management facility by conveyer belts. Low water-content tailings pose fewer engineering risks, such as dam failure (Luppnow, 2013). An added
Radioactive and other environmental contamination incentive is the recuperation of process water, which is encouraged for resources conservation reasons and may even be essential in arid environments with limited water supply (Figure 1.4). The main stream of tailings would have much of the acid–alkali-leachable constituents removed. However, the sludges from the stripping process will contain all non-uranium heavy metals and radionuclides.

It should be noted that such tailings arise from all wet milling processes for metal ores. They usually contain all (heavy) metals and radionuclides from the original ore, minus the target metal(s). As only the uranium will have been removed, the amount of radioactivity in them may still be considerable. Although the milling process does not increase the concentrations by weight compared to the original ore, it may have changed the mineralogical and chemical form, making constituents of concern more mobile. Modern ore processing tries to minimize the volume of waste streams (IAEA, 1999) and to render contaminants less mobile.

**Decant waters** from the tailings pond may contain radionuclides, (heavy) metals, and other toxic compounds, although the neutralization with limestone and the stripping process will have precipitated a considerable fraction of them. Operating tailings ponds are uncovered, and any atmospheric precipitation will add to the water balance. The decant water may also still be acidic, depending on the effectiveness of the neutralization step and whether there are any sulfide-bearing minerals left in the tailings (Metzler & Ritchey, 2011). As a consequence, decant water almost always has to be treated before being released into the environment. The resulting treatment sludges are returned to the tailings pond. While the treatment of the decant waters is part of the mill operation, it may pose considerable organizational and stewardship challenges after its closure. The use of passive treatment systems, such as constructed wetlands, has been proposed as a low-technology solution, but still requires the adequate management of the biomass that has accumulated the radionuclides and heavy metals (IAEA, 2004c).

![Dry stacking of tailings in Arlit (Niger).](image)

*Figure 1.4* Dry stacking of tailings in Arlit (Niger).

Photograph: W.E. Falck.
Auxiliary processes, such as the on-site production of sulfuric acid, will result in liquid and solid wastes. For the solid wastes, either dedicated impoundments are constructed, or they are disposed of in the tailings ponds. If the mine is close by, waste streams of similar types and disposal requirements may be combined.

Gaseous wastes, such as ventilation air, are normally released directly into the environment. They may need to be filtered to remove dust particles that can act as vectors for radioactivity. The resulting filter cakes need to be disposed of adequately in compliance with radiation protection and other environmental impact legislation. A discussion of the use of the atmosphere as a repository for oxidized carbon (CO₂, CO) and other GHG discharges is beyond the scope of this book.

1.2.3.3 Impact pathways from milling residues

As uranium ore milling is a controlled practice from a radiation protection perspective, workplace exposures are not discussed in this section, nor are industrial-type accidents that may occur during operation.

Geotechnical issues. Tailings are difficult-to-manage materials, owing to their high water content and uniform grain-size distribution (Figure 1.5). Unless paste technology or dry stacking (see above) is used, freshly deposited tailings are not stable and have to be retained in an engineered pond that relies on the stability of the surrounding dams (IAEA, 2004b). A breach of a dam, for example, due to erosion or ground instability, can have catastrophic effects (Azam & Li, 2010; http://www.wise-uranium.org/mdaf.html), such as flash floods and mud flows downstream. Tailings ponds may also overflow when the water management system breaks down or its capacity is exceeded due to persistent rainfall. Apart from the immediate physical

![Figure 1.5 Potential environmental impacts from uranium mill tailings.](image-url)
impacts, long-term problems will arise from any tailings mass dispersed into the surrounding environment. The tailings will be difficult to recover because of their amount and consistency. Long-term contamination of (agricultural) soils, contamination of groundwater due to infiltration of leachates, generation of contaminated dusts that can be inhaled and ingested, and direct exposure will be the results (Moncur, Ptacek, Blowes, & Jambor, 2005).

**Dust.** Particularly during the dry season, uncovered tailings may dry out sufficiently to give rise to dust dispersal. The dust may settle on surrounding fields and plants, opening up pathways for direct exposure by contact and for ingestion. Contaminants may be leached from the dust by atmospheric precipitation and may reach groundwaters. The dust may also be washed into surface water courses and may accumulate in bottom sediments, from where it may be eroded again and further dispersed.

**Uncollected and untreated drainage** will reach surface water courses and groundwaters. The drainage can have very low pH values, due to incomplete neutralization at the end of the milling process or due to secondary acidification by the oxidation of sulfur-bearing minerals (acid drainage) in the tailings. Acid drainage will promote the dissolution and migration of radionuclides and heavy metals. These contaminated waters may be ingested directly or used for irrigation purposes. Low-pH discharges into surface waters can also have an adverse impact on aquatic life.

**Ventilation** discharge points of the milling plant have to be selected so that a sufficient dilution by dispersion is ensured to prevent the local population from receiving impermissible doses from it. Uncovered tailings ponds may release radon and thoron, if the tailings still contain radionuclides of the relevant decay chain. Under quiet weather conditions, radon may accumulate in valleys or other topographical depressions, in which the ponds often are located, resulting in exposures further down-valley (Steck et al., 1999).

**Residues,** such as tailings, are attractive as aggregates for the preparation of concrete and there are various examples of unauthorized removal of such materials for construction purposes (USEPA, 2008; Chapter 4). This may result in direct exposures from walls or floors/ceilings and radon accumulation in homes. In other instances, tailings material and mining residues have been used to ameliorate garden soils, resulting in contaminants being ingested through food plants (Marks, Denham, Cross, & Kennedy, 1984).

## 1.3 Uranium mining and milling (UMM) legacy sites and their remediation

### 1.3.1 The scope of the issue

Since some mines and mills may have been in operation for many decades, sometimes with different operating companies, it is often not so easy to distinguish between sites that are part of the current operation and legacy sites. Although waste and residue management facilities that have been operated in the more distant past may not fulfill modern requirements with respect to environmental safety and thus may require remediation, they are part of the current operation (IAEA, 1997b). Therefore, the current operator is legally and financially responsible for their maintenance and
eventual remediation. On the other hand, there are many uranium mining sites worldwide that technically have become “orphaned”, as the mine operator, often a state-owned company, has ceased to exist, particularly after the fall of the Iron Curtain in 1989. In most cases, the respective government has assumed responsibility for such sites. This does not necessarily mean that the government has the financial resources and technical capability for their remediation. Particularly in the former Eastern Bloc countries, such sites posed a threat to the environment and to the surrounding population (IAEA, 2005b; Jacubick, Kurylchyk, Voitekhovich, & Waggitt, 2008), but also are of concern in the United States, with its many abandoned mines (USEPA, 2008; Chapter 5). International aid programs under the auspices of the European Union (EU) and the IAEA have helped to assess the extent of the problems and to implement solutions. In the United States, the Uranium Mine Tailing Radiation Control Act (UMTRCA, 1978) provided for the management of the uranium-mining legacies in this country.

To enumerate these sites is very difficult, as many of them have been mere experimental diggings and exist in most countries with uranium-bearing host rocks (OECD-NEA/IAEA, 1999). The multitude of such sites, not only in the Eastern Bloc countries, but also in the United States and various Western European countries, has necessitated a prioritization of actions based on risk assessments.

1.3.2 The objectives and limitations of remediation

The IAEA Safety Glossary (2007) defines remediation as “any measure that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans. Complete removal of the contamination is not implied. The often read terms rehabilitation and restoration may be taken to imply that the conditions that prevailed before the contamination can be achieved again, which is not normally the case (e.g., owing to the effects of the remedial action) and should not be used”. Remediation is an intervention. In radiation protection, an intervention is any action intended to reduce or avert exposure, or to reduce or avert the likelihood of exposure to sources that are not part of a controlled practice or are out of control as a consequence of an accident. The analogous applies to nonradiological contamination.

The goal of remediation is the timely and progressive reduction of hazard and eventually, if possible, the removal of regulatory control from the mining or milling site without restrictions (“free release”). Remedial measures should do more good than harm and should provide optimized arrangements for protection to maximize the net benefit to society. However, there are situations in which the removal of control from the area cannot practicably be achieved; in such cases, at least the unacceptable risks to human health and the environment should be removed while the sites remain under institutional control, that is, stewardship (see Section 1.4). The objective of remedial actions is to reduce the doses to exposed individuals or groups of individuals, to avert doses to individuals or groups of individuals that are likely to arise in the future, and to prevent or reduce environmental impacts from the radionuclides (and other contaminants) present in the contaminated area. These objectives will be achieved by either removing a hazard, for example, the
source of contamination, or by modifying or interrupting the pathway of exposure, that is, by risk reduction. However, radiological contamination may often be of far less concern at uranium mining and milling (UMM) sites than other types of hazards.

### 1.3.3 Remediation strategies and techniques

A diverse portfolio of remediation strategies and techniques is available today that can be applied to uranium mining and milling sites (Figure 1.6). The baseline option against which other options are compared with respect to feasibility, effectiveness, cost, as well as public and regulatory acceptance is always monitored non-intervention (IAEA, 2006a; USEPA, 1999b, 2007a, 2007b). This option is based on the resilience of the surrounding environment against impacts from such sites. Sites that have been reasonably stable over several decades are likely to remain so and may not need immediate invasive attention. However, their likely long-term risk will have to be assessed.

**Isolation.** Many remediation techniques, on the other hand, aim to improve the resistance of the sites against the actions of the surrounding environment. Capping of mine wastes and tailings ponds reduces the ingress of precipitation and thus reduces the vector of contamination. It also reduces materials loss due to erosion and suppresses radon exhalation. Underground *in situ* barriers will reduce the spread of contaminants into groundwaters. They may be needed around open-pit mines or to prevent downstream contamination from unlined tailings ponds. Permeable reactive barriers serve a similar purpose (Blowes, Bain, Jeen, & Hughes, 2008; Csövári, Földing, Csicsák, & Frucht, 2008; USEPA, 1999a), sometimes as part of a pump-and-treat scheme for contaminated groundwaters. Tailings ponds often release draining waters for decades due to the slow dewatering of the stacked material. Thus, the water has to be collected in engineered draining systems and treated before release. Low-technology solutions such as phyto-treatment plants have been tried out, but are not reliable under all conditions. A disposal route for the separated radionuclides and other contaminants has to be available. The engineering features that provide for isolation (e.g., dams, caps, liners) have to be maintained periodically to ensure their effectiveness, which provides particular stewardship challenges (see below).

**Figure 1.6** Conceptualization of remediation strategies.
Relocation. Excavation and relocation of mine waste or tailings would be undertaken only under rare circumstances due to the large volumes involved. For instance, the Lichtenberg open pit of the Wismut operation in Saxony (Germany) was backfilled with materials from various surrounding waste heaps (Figure 1.7). Another example of such a large-scale relocation operation is the tailings pond upstream from Moab (Utah, USA) (http://www.moabtailings.org) that is under the threat of erosion from

Figure 1.7 (a–c) Backfilling the open-pit mine Lichtenberg with material from various mine waste dumps. The waste material was selected such that the original geological sequence was reconstituted as far as possible.  
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the Colorado River. At many operations, smaller waste heaps and tailings ponds have been excavated and merged into larger ones, to reduce the number of sites for which institutional control stewardship activities are needed.

**Reworking.** Considering that extraction techniques were often less efficient in the past than they are today, the reworking of old tailings or below-grade ore dumps can be of economic interest, and they can form part of a remediation program or even its incentive. Whether it is a viable option depends on the specific local circumstances and the availability of a processing plant for the materials. The commercial viability may be further improved by the presence of other metals of interest that can be extracted. It is also important that the resulting residues are easier and safer to dispose of with reduced probability of remobilization of toxic constituents than the original residues.

**1.3.4 Nontechnical considerations**

The choice of remediation strategy and technology and associated stewardship programs is determined not only by technical and economic considerations, but also by their respective public acceptance (IAEA, 2002a). The granting of a “social license” (Thomson & Boutilier, 2011) for particular remediation projects will involve deliberations with respect to the envisaged future land use, residual risks, visual aspects of the sites, regulatory acceptability of the proposed technology, long-term liabilities/stewardship needs, and collateral impacts of the remediation process (Falck et al., 2014b; IAEA, 2006b). There have been cases in the past in which stakeholders (the public; political decision makers) objected to the continuation of uranium production as part of the remediation process. In consequence, solutions that are desirable from a technological or economic point of view may not necessarily find the required acceptance.
1.4 Life-cycle management of UMM sites

1.4.1 A change of paradigms

Uranium mining and milling projects, in line with the development in other areas of the raw materials industry, increasingly adopt a life-cycle management approach (Figure 1.8).

This means a move away from the “end-of-the-pipe” treatment of environmental and socioeconomic impacts (Falck, 2009). Life-cycle planning facilitates decommissioning and reduces the need for remediation (IAEA, 2009). Decommissioning and remediation costs are fully internalized, and hopefully few or no unresolved problems are left to future generations. Life-Cycle (Impact) Assessments also help to internalize noneconomic costs, which will result in less material being mined, less waste to be managed, and hence lower impacts downstream in the processes. A life-cycle perspective will also change the approach to facility design and operation. Facilities, particularly those for the management of residues, will be designed with their decommissioning and long-term stewardship in mind. In this way, these future challenges will already be considered at the design stage, rather than faced only at the closure stage. Overall, this should lead to lower long-term impacts.

1.4.2 Mining residues

In the management of mining and milling residues, one needs to distinguish the operational phase and the post-closure phase of the life cycle of mines and mills. In each phase, different objectives, criteria, and sets of technical parameters will guide the selection of management solutions (OECD-NEA/IAEA, 2002). The operational phase is characterized by continuous care and maintenance; in contrast, the post-closure phase solutions have to be selected that render the residues safe with a minimum of maintenance. In the past, these paradigms often have not been followed, resulting in legacy sites that may require remediation (see Section 1.4).

Overburden and barren rock is stored or disposed of at locations that minimize transport distances and according to the availability of land. The latter may not be a very constraining factor in remote, sparsely populated areas. There, a location that minimizes the risk from leaching-out contaminants may be chosen, avoiding zones of fractured bedrock or selecting areas with less pervious geological formations. A bottom liner may be needed to collect acid drainage and prevent it from seeping into surface and groundwaters. Such liners typically consist of compacted clay. Geomembranes may also be used. A gravel drainage or geotextile...
layer above the liners will facilitate the collection of seepage waters for proper management. In practice, liners under spoil heaps do not seem to have been used very often in the past. Constraining factors include the cost of and availability of suitable lining materials, such as dense clays. The clays used have to be tested for their geochemical compatibility with the drainage waters, as these may degrade their beneficial properties.

The grading of slopes usually is chosen so as to minimize the footprint of the site. However, one may need to optimize between the cost of stacking higher and the footprint. The load-bearing capacity of the underlying geological strata may be a limiting factor for stacking height, as could be esthetic requirements. The grade of the slope is normally the one that develops naturally for a given type of material, moisture content, and compaction rate. Erosion tends to flatten these slopes, so that spoil heaps have to be maintained periodically to re-establish the desired slopes. Once a decision has been made that no further mine waste will go into a particular facility, the slopes are graded to be comparable to those of the natural surroundings (IAEA, 2002b).

Erosion, acid drainage, and dust can have significant impacts, but they can be controlled by covering and vegetating inactive areas of spoil heaps. Covers and vegetation reduce the amount of rainwater infiltration and oxygen ingress. For the same reason, covers enhance the geotechnical stability of the slope. Covers can also be designed to trap radon and thoron and thus allow these to decay before they reach the atmosphere. The design of the covers has to be adapted to the surrounding ecosystems, its soil profile, and vegetation type. The cover design may range from a simple layer of rubble in arid areas to a complex sequence of layers that mimic the soil in the surrounding ecosystem (IAEA, 2006b). Periodic monitoring and maintenance ensure the integrity of cover and vegetation (IAEA, 2002c). The roots of trees and other plants can penetrate the covers and compromise their function, and therefore need to be removed. Likewise, burrowing animals, such as rabbits, can enhance the erosion of covers and need to be controlled. Layers of rubble are elements of cover design intended to discourage roots from penetrating and animals from building burrows. The effects of human penetration, accidental or intentional, may also need to be repaired. In areas of active disposal, the construction of such covers is not practical, but a cover with geotextiles that can be taken up before a new layer of waste is deposited may reduce the impacts noted above.

**Subgrade ore** that is retained for a time when its milling may become commercially viable needs to be stored under conditions that prevent auto-leaching by acid drainage formation. In other words, it needs to be covered, and bottom liners to collect contaminated drainage must be constructed. Alternatively the storage site may be designed as a heap-leaching facility (either with or without the addition of lixiviants), where the uranium-enriched drainage is collected and added to the milling process stream. The leached residues would be transferred to a spoil heap or co-disposed with the mill tailings. Subgrade ore that has not been milled by the time that a mine and mill are destined for closure may require special treatment to prevent impacts from auto-leaching. A capping, at least, needs to be put in place.
1.4.3 **Mill tailings**

Since waste management is an unproductive activity from a commercial point of view, operators understandably seek the least costly option for constructing tailings ponds that is in compliance with the applicable mining and civil engineering regulations (IAEA, 2004b). The use of natural depressions as sites for tailings ponds is an obvious choice. In hilly and mountainous terrains, often a valley was chosen and blocked off with a dam, behind which the tailings were emplaced. Sometimes small lakes are used for this purpose (subaqueous tailings disposal) or a mined-out pit. The rationale was that the temperature-induced stratification of a deep lake, with cold waters remaining at the bottom, would prevent any radionuclides and other constituents from entering the biosphere. A water layer above an active tailings pond would also delay radon escape until it decays (Courbet et al., 2013).

Where such landscape features are not available, above-ground tailings ponds surrounded by dams (“turkey nests”) have to be built. An infrequently used option is backfilling the tailings into underground mines. Paste tailings conditioned with binders would be most suitable for this (Moran, Christoffersen, Gillow, & Hay, 2013). Although the resulting backfill mass would have a low permeability and, therefore, low leachability, the addition of binders would be detrimental for the materials and energy balance of mining and milling operation. There are also concerns that the $^{226}$Ra content could lead to enhanced radon concentrations in the mine air (Clausen & Archibald, 1983). For other tailings, the drainage waters would need to be managed adequately to prevent later impact on the flooding waters, once the mine is closed out.

Tailing ponds present a considerable engineering and long-term management challenge (IAEA, 2004b). Suitable dam materials and the construction of the retaining dams are important cost factors. Similar to hydropower and irrigation pond dams, these dams are in permanent contact with water and therefore need to be water-proofed. To distribute investments over time, dams are often built in stages and heightened according to operational needs. Different strategies to increase the height and minimize the use of additional building materials are used. Thus it is possible to built a new dam partly over the impounded tailings, if their dewatering has progressed sufficiently (Figure 1.5). An important factor to consider is the load-bearing capacity of the underlying strata. Dams also need to be keyed well into the sole and flanks of the valley to prevent them from being pushed out of place by the tailings mass. Injection curtains may be needed to prevent the flow of porewaters around the dam and through the surrounding rocks, thus compromising the keying-in of the dams. Like all earth dams, tailings dams are vulnerable to earthquakes. The engineered structures of tailings dams require constant monitoring and maintenance to ensure their integrity (IAEA, 2002c).

In the past, tailings ponds were typically built without bottom liners, using the permeability of the underlying ground to aid the dewatering. This means that untreated drainage waters entered the subsurface and reached the groundwater. Today, tailings ponds are constructed with liners and (bottom) drainage systems to collect the drainage water for treatment. A variant to this is the “pervious surround” system developed in Canada (Donald, Welch, Holl, & Landine, 1997). Here the tailings are dewatered and mixed with lime to achieve a permeability lower than that of the surrounding rocks.
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This reduces the leaching-out of the material, albeit at the expense of an increased energy and materials footprint.

Naturally Occurring Radioactive Material (NORM)-containing tailings other than uranium mill tailings, for example, phosphogypsum, have been and still are being discharged into the sea, although this practice is being discouraged (IAEA, 2003).

1.4.4 Decommissioning of mines and mills

It has been common practice in mining, for centuries, to abandon the site, often including the surface structures, without any particular measures to decommission it. This has often resulted in orphan and legacy sites. The reason is that after the ore had been exhausted, the mining companies often ran into financial difficulties, and resources for an orderly closure were no longer available. Today, before a mine license is granted, some form of financial security, for example, bonds deposited, is usually required that will cover decommissioning and remediation costs (IAEA, 2006b). In practice, in many non-uranium mining examples, the objectives and purposes of remediation were not very well understood or acknowledged by either the operators or the licensing authorities, and the financial instruments were insufficient, allowing only for cosmetic actions such as revegetation. For modern uranium mining and milling projects, a full life-cycle management plan will be developed before any mining commences. The “polluter pays principle” is applied analogously to mine sites. Stepwise decommissioning of mined-out areas and filled waste management facilities distributes the cost and work over the operational time of the mine and mill, rather than accumulating it at the end of the lifetime (Falck et al., 2009; IAEA, 2009).

The orderly closure of both underground and open-cast mines aims at making safe the mine works themselves, as well as the residue management facilities (IAEA, 1994, 1995, 2010). The objective is to prevent uncontrolled ground movements, such as subsidence, and to ensure the slope stability of pits, waste rock dumps, and tailings ponds. Necessary measures may include backfilling and sealing of shafts and other underground mine workings. Before open mine works are closed, normally all materials potentially hazardous to the groundwater, such as oils, transformer fluids, and explosives, have to be removed and brought to the surface for orderly recycling or disposal. Slopes may need to be re-graded to a shallower inclination so as to reduce the risk of erosional losses of stability. Waste rock dumps are best covered and re-vegetated as soon as they are not needed anymore in the operation. This reduces end-of-operation remediation costs and can make use of existing mine infrastructure and personnel. Sealing and backfilling of mined-out areas has the objective to reduce groundwater circulation after flooding, thus reducing the leaching of hazardous substances and the AMD generation potential (IAEA, 1997a). Strategic sealing and backfilling during operation also reduces the radon load in the mine air and thus the ventilation needs and above-ground impacts.

Most mine operations are below the local groundwater table and require constant pumping to keep the mine dry. Over the years, this will have resulted in a considerable depression cone in the surrounding aquifers, particularly in the case of open-cast mines. Flooding of the mines has to proceed in a controlled way that allows the re-establishment of the pre-mining water table. Letting a mine flood in an uncontrolled way can have
severe impacts on the surrounding hydrological regime. It may result in locally reversed groundwater flows and drying up of local rivers. It can also lead to AMD generation and dispersal. Uncontrolled flooding can also compromise the geotechnical stability of underground and open-cast mines due to an uncontrolled re-equilibration of stresses. The controlled flooding, particularly of open-cast mines, is a process that may take many years.

The closure, decommissioning, and remediation of ISL mines pose specific problems. The hydraulic regime established for the mine has to be maintained and operated as a pump-and-treat remediation facility; that is, the acidic leaching solution has to be neutralized and then re-injected into the ground (USNRC, 2007, 2009). This means that the uranium recovery plant will have to operate for several years beyond the commercially viable point. There has to be a disposal or market route for any metals (including uranium) removed during the neutralization step. The sale of the recovered metals can contribute to covering the decommissioning and remediation costs. Of particular concern are hydraulic shortcuts among several aquifers, some of which may be used for drinking water abstraction. Although the host rock may not have been suitable for drinking water production in any case, differences in hydraulic head may lead to cross-contamination into aquifers without mineralizations along inadequately sealed boreholes. This is not a problem specifically associated with ISL systems, however. The shafts of deep mines may also penetrate several aquifers and need to be sealed when the mine is decommissioned and flooded.

Above-ground structures of the mine and mill need to be decontaminated, if necessary, before they can be demolished and removed. Decontamination will ensure that most of the materials can be recycled or re-used. Whether foundations and similar structures have to be removed depends on the planned future land-use for the site. In some cases, infilling may be sufficient. When designing new facilities, decommissioning needs can already be taken into account. This will facilitate the eventual decommissioning.

Remediation of mining and milling facilities often is a long-lasting process and may require a variety of installations to handle and treat materials (IAEA, 1998). The careful integration of decommissioning and remediation will often facilitate both processes (IAEA, 2009). During decommissioning only those plants, structures, and buildings will be removed that are not needed anymore. Conversely, certain installations of the mine and the mill can be used for managing wastes and residues that arise out of remediation and decommissioning activities. These typically include sorting, water treatment, and conditioning plants. Certain buildings and infrastructure, such as the power and water supply, will be retained until the remainder of the project is completed. This integration will reduce the decommissioning and remediation costs by creating synergies (Falck et al., 2009).

### 1.4.5 Long-term management (stewardship) of UMM sites

Any man-made structure above ground has significant amounts of potential energy stored in it. The second law of thermodynamics mandates that this energy be dissipated unless more energy is spent on maintaining the status quo. In other words, such structures require maintenance forever (IAEA, 2006b). When designing waste disposal sites it is therefore wise to minimize the amount of potential energy stored in them, for instance, by going underground (Figure 1.9).

The classical engineering paradigm in waste disposal is to design structures to contain wastes. This inevitably introduces chemical and physical potentials into the
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environment, as the structures are made from alien materials and the wastes themselves are alien materials (Figure 1.10). UMM residues management not only is an engineering task, but requires a good understanding of the long-term geological, geochemical, and hydrological processes in the host geology. Adaptation to the local situation will help

![Diagram](image1.png)

**Figure 1.9** The paradigm of engineering with nature, not against it. From IAEA (2006b) with permission.

![Diagram](image2.png)

**Figure 1.10** Long-term stewardship challenges. Modified from IAEA (2006b), with permission.
to extend the time horizon over which the various potentials will be dissipated, perhaps well beyond a time horizon over which active maintenance can reasonably be expected.

Modern approaches to mining, including uranium mining, are based on a full life-cycle approach. In this, plans are made for the long-term management and long-term safety of such sites right from early days of project development. This allows, for instance, introduction of long-term stable engineering solutions, thus preventing costly re-engineering and remedial actions. Assessing all material flows over the life cycle will help to reduce the amount of materials moved around, which will also result in cost savings. Modern mining process engineering under development (see, e.g., the I2Mine project, http://www.i2mine.eu) aims to reduce the amount of unwanted materials brought to the surface with a view to reducing the amount of material requiring long-term management. A life-cycle energy and material flow assessment will also help to reduce the overall impact of UMM operations.

Given that any engineered surface structure, such as tailings ponds or (covered) residue heaps, will require periodic monitoring, surveillance, and maintenance after their closure and after active UMM has ceased (IAEA, 2002; Kreyssig, Sporbert, & Eulenburg, 2008), the question arises as to who will be responsible for these. The same question arises for (near-)surface radioactive or hazardous waste repositories and has been debated extensively in this context (OECD-NEA, 2007). Looking back in history, it is rather unlikely that a certain government structure or other institution will survive beyond a 100-year time frame. There are notable exceptions, in which institutions and their infrastructure actively survived for hundreds of years, such as the Christian Church, the Academie Française, the British Monarchy, and others. There are also many counter examples for institutions that persisted for centuries and then have disappeared, particularly over the past 50 years or so. One can note that there is always a special spiritual relationship between the public and the institution and perhaps also its physical infrastructure (OECD-NEA, 2007). However, it is nearly impossible to deliberately create such spiritual long-term relationships; they develop, or do not develop, naturally. Reflecting on these difficulties, organizations such as the OECD-NEA (OECD-NEA, 2010) and the IAEA (IAEA, 2006b) came to the conclusion that, rather than focusing on lengthy time scales, it is better to focus on a horizon of two to three generations (=30–60 years), rather than on “archaeological” (=1000+ years) or even “geological” (=10,000+ years) time horizons.

1.5 Future trends

1.5.1 Impacts as a function of the resource type

Uranium mining, in line with other metal mining, is likely to move toward lower ore grades and deeper deposits, as the richer and shallower deposits have been mined out. The majority of uranium mineralizations that have been mined in the past and that are currently mined are associated with sandstones, although considerable mineralizations may be also found in more difficult-to-mine hard rocks. Projections on the likelihood of discovering rich deposits vary (OECD-NEA/IAEA, 2012), but it cannot be ruled out that rich deposits are found, considering the relatively low prospecting expenditure since the late 1970s, compared to that for oil and gas, for instance (Falck, 2009).
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Such deposits, however, would be at greater depth than those mined currently. Lower ore grades mean that more material has to be moved and processed, which in turn results in potentially greater impacts, as impacts are related to the amount of material mined. For these reasons, the construction of new open-cast mines is becoming less likely in the future. Therefore, the associated large-scale impacts due to the need for managing large volumes of overburden will become less. Mine operators will balance the economic, operational, and other advantages or disadvantages of bringing materials to the surface against using them as backfill underground. Life-cycle impact analyses increasingly will inform the decision-making processes (Falck, 2011).

1.5.2 Improved deep mining operations

Not bringing mined-out material to the surface improves the energy balance of the operation, but may have certain operational disadvantages, as intermediate storage volumina have to be found underground. Use of tailings as backfill would obviate the need for surface tailings ponds, but has higher energy requirements due to longer transport routes, the need for more complex modes of conveyance, and certain conditioning needs. These are issues that arise not only in the uranium mining industry, but in any type of mining industry. They are currently the subject of various national and international research projects, including the European Commission 7th Framework project I²Mine (http://www.i2mine.eu). This project investigates the implications of having to mine deeper and in harder rocks. The energetic requirements for mining and milling hard rocks are certainly higher than for other types of rock, such as sandstones. The project also aims at developing techniques and procedures for moving at least part of the milling process underground. In consequence, the mining and milling residues will remain underground. It is anticipated that the development toward less visible mines will be honored by stakeholders with an easier process to obtain the “social license to operate” (Falck et al., 2014a). In any case, licensing of uranium mines remains a challenge (IAEA, 2001b).

To reduce exposure of the miners to the harsh environment in deep mines, modern mines are likely to be more remotely operated whenever possible. In some modern uranium mines (e.g., Cigar Lake in Canada), this development is already taking place, due to the high dose rates received otherwise by miners.

1.5.3 Increasing importance of in situ leaching (ISL) operations

Nearly two-thirds of the uranium produced now is produced from ISL mine operations (OECD-NEA/IAEA, 2014). This trend is likely to continue, as long as mineralizations in porous host rocks can be mined. ISL is not feasible where the uranium minerals form a constituent of a largely impermeable rock matrix. In matrices, such as granites, even permeability-enhancing techniques, such as fracking, would not provide sufficient access to the uranium minerals that need to be dissolved. Otherwise, given diligent process control by the operator and adequate regulatory oversight, ISL has the potential for low-impact mining (NRC, 2009). From a resource use–efficiency perspective remains the concern that the percentage of uranium recoverable from the formation by ISL is smaller than when using traditional mining techniques. This is a
problem that is also faced by other mining industries that use ISL, namely, the copper mining industry, and research and development efforts are being made to improve the effectiveness of the process.

1.5.4 Changing paradigms in the mining industry as a whole

Not the least by facing increasing difficulties to obtain the social licensing, the mining industry aims to avoid the mistakes of the past that have created long-term liabilities (Waggit, 2011). The construction of surface repositories for mining and milling residues probably can never be completely avoided, but the amount of material disposed of in these repositories can be kept to a minimum and the materials can be made more inert. A full life-cycle approach to designing and managing mines and mills will help to reduce the need for stewardship after the end of the operation. Although mining and environmental legislation do exist in many countries, regulatory oversight and the enforcement of legislation often leaves much to be desired, particularly in some less-developed countries. Many uranium mining companies operate globally and thus are under the scrutiny of globally operating environmental NGOs as well. European Union regulations stipulate that mining companies that have their legal seat in the EU have to comply at their overseas operations with EU standards and regulations. Large mining companies also subscribe to voluntary standards of environmental and social conduct, for example, through the International Council on Mining and Metals (ICMM) (http://www.icmm.com). Of concern, however, are the many so-called “junior” mining companies that often operate only one mine with a short lifespan. For them, there is little incentive to comply with voluntary codes of conduct and good practice. Such mines still have the potential to become “orphaned” at some stage, although the license to operate may have been coupled with deposits for remediation.

As has been noted above, a fully comprehensive life-cycle management approach becomes increasingly the planning guideline in the mining industry, including the uranium mining industry. This leads to the anticipation of (environmental, societal) problems before they actually manifest themselves, rather than their remediation. The improved internalization of life-cycle costs of producing uranium will lead to less cost that has to be borne indirectly, for example, through tax payers’ money being used for legacy management. Avoiding sources of impact will also avoid the associated impacts, the costs of which are usually impossible to internalize in retrospect.

1.6 Sources of further information

Probably the largest body on technical and regulatory guidance for uranium mining can be found in the various publications produced by the International Atomic Energy Agency (IAEA), namely, in their Nuclear Fuel Cycle and Materials, Waste Technology, and Waste Safety Sections, respectively (http://www.iaea.org). Many of the more recent and important publications are listed in the references section below.

Together with the OECD–Nuclear Energy Agency (http://www.oecd-nea.org), the IAEA also produces the so-called “Red Book” on uranium resources and demand that details the various uranium production activities in their Member
States (OECD-NEA/IAEA, 2012). The work is supported by the so-called “Uranium Group” of experts from the respective countries.

To facilitate the exchange of knowledge among practitioners, regulators, and other interested stakeholders, the IAEA set up a network of experts under the name ENVIRONET (Fernandes & Carson, 2011).

The International Mine Water Association (http://www.imwa.info) brings together many important players in mining, consulting, and research, some of whom have a uranium mining background.

A comprehensive resource on uranium mining projects worldwide is the Web site of the privately operated World Information Service on Energy—Uranium Project (http://www.uranium-wise.org).

Recognizing its legacy of UMM sites, the United States passed, in 1978, the so-called Uranium Mill Tailings Radiation Control Act (UMTRCA), resulting in the UMTRA project (see, e.g., http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/mill-tailings.html). Since then, a large body of remediation experience, mainly in arid areas, has been accumulated.

One of the most daunting tasks in terms of remediation was faced in Germany by the states of Saxony and Thuringia, following the decision in 1989 to abandon uranium mining. The state-owned successor company (http://www.wismut.de/en/) to the former mining company has accumulated a wealth of experience in the area of remediation.

References

Note: extensive use was made of IAEA reports because they summarize the current state of knowledge at the time of their writing, including many case studies, contain many further references, and are easily accessible through the Internet.


Environmental Remediation and Restoration of Contaminated Nuclear and NORM Sites


