Nuclear Development
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Managing Environmental and Health Impacts of Uranium Mining





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Managing Environmental and Health Impacts of Uranium Mining

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Foreword

Uranium is the raw material used to produce fuel for nuclear power plants that generate significant amounts of electricity with life cycle carbon emissions that are as low as renewable energy sources. However, the mining of this valuable energy commodity remains controversial, principally because of environmental and health impacts associated with the early years of uranium mining. Maximising production in the face of rapidly rising demand was the principal goal of uranium mining at the time, with little concern given to properly managing environmental and health impacts.

Today, societal expectations and regulation of the industry are directed much more towards radiation protection, environmental stewardship, health and safety. With over 430 operational reactors in the world, nuclear fuel will be required for many decades in order to meet requirements to fuel the existing fleet and demand created by new reactors, given the projected growth in nuclear generating capacity, particularly in the developing world. New mines will in turn be needed. As a result, enhancing awareness of leading practices in uranium mining is increasingly important.

This report aims to dispel some of the myths, fears and misconceptions about uranium mining by providing an overview of how leading practice mining can significantly reduce all impacts compared to the early strategic period. It also provides a non-technical overview of leading practices, the regulatory environment in which mining companies operate and the outcomes of implementing such practices.

Societal expectations related to environmental protection and the safety of workers and the public evolved considerably as the outcomes of the early era of mining became apparent, driving changes in regulatory oversight and mining practices. Uranium mining is now conducted under significantly different circumstances, with leading practice mining the most regulated and one of the safest and environmentally responsible forms of mining in the world.

In support of this statement, this report provides an overview of the evolution of mining practices and outlines how health and environmental impacts of leading practice uranium mines are managed and minimised. All aspects of the full life cycle of a mine are covered, from the time that a deposit is considered to be of economic interest for mining to the time that mining is completed, the facility is closed and remediated and control of the leased land is returned to the landowner, usually the government. Case studies are included to further demonstrate the scale of the changes undertaken as well as to outline the outcomes of historic and modern mining practices.

This report provides a factual account of leading practices in order to inform public debate on uranium mine development and to provide policy makers with a framework of approaches that should be undertaken to ensure that uranium mining is conducted in a safe and environmentally responsible manner. Key components in achieving this goal include the establishment of an appropriate regulatory framework, planning for closure before the mine begins production, requiring financial assurance from companies to cover the costs of closure and remediation, application of leading practices to minimise radiation exposure of workers and the public, protection of water resources and the safe, long-term disposal of tailings and problematic waste rock. Public consultation and information sharing, environmental impact assessment and environmental monitoring

throughout the life cycle of the mine facility are also shown to be crucial components of this framework.

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Executive summary

Producing uranium in a safe and environmentally responsible manner is not only important to the producers and consumers of the product, but also to society at large. Given expectations of growth in nuclear generating capacity and associated uranium demand in the coming decades – particularly in the developing world – enhancing awareness of leading practice in uranium mining is important. This report provides a non-technical overview of the driving forces behind the significant evolution of uranium mining practices from the time that uranium was first mined for military purposes until today.

Uranium mining remains controversial principally because of legacy environmental and health issues created during the early phase of the industry. Today, uranium mining is conducted under significantly different circumstances and is now the most regulated and one of the safest forms of mining in the world. This report compares historic uranium mining practices with leading practices in the modern era, and provides an overview of the considerable evolution of regulations and mining practices that have occurred in the last few decades. Case studies of past and current practices are included to highlight these developments and to contrast the outcomes of historic and modern practices.

With over 430 reactors operational worldwide at the end of 2013, more than 70 under construction and many more under consideration, providing fuel for these long-lived facilities will be essential for the uninterrupted generation of significant amounts of baseload electricity for decades to come. While phase-out plans have been announced by a few countries following the 2011 accident at the Fukushima Daiichi nuclear power plant (NPP) in Japan, the long lifetimes of existing and future NPPs will prompt an increase in uranium mine production. The issue of sourcing uranium from producing countries with an acceptable regulatory framework and from mining companies applying leading mining practices is therefore becoming increasingly important considering that a number of countries with NPPs or plans to construct them have no domestic uranium mining.

Chapter 1 of this report provides an introductory overview of the life cycle of a mine, examines issues arising from mining and outlines why uranium mine production is expected to expand in the coming years. Chapter 2 addresses the key operational challenges that must be addressed in modern uranium mining since negative impacts of past practices arose in these key areas. The **health and safety of workers and the public** is one such critical area. Past practices led to serious consequences that remain a fundamental part of the negative sentiment against uranium mining today. How these issues are currently managed is outlined in order to illustrate the significant improvements that have been achieved through the implementation of leading practices.

Water quality impacts of historic mining operations were also in some cases severe and a comparison of essentially unregulated past practices to ways in which leading practice operations manage water resources is provided. A description of how the fastest-growing method of uranium mining in the world – *in situ* leach (ISL) mining, sometimes referred to as *in situ* recovery or ISR – is planned and conducted to protect surface and groundwater resources is included here, since historic ISL operations at times had a significant impact on groundwater resources. A case study of environmental impact assessments demonstrates the care with which ISL mining must be planned.

The long-term management and disposal of waste arising from ore processing was also an important part of strategic era mine legacies. Current approaches to **tailings** management and disposal are therefore outlined to demonstrate how even tailings from the most challenging high grade ores can be managed in the long term. Another legacy from this strategic, military production period is **waste rock**. Modern approaches to the management and disposal of problematic waste rock that minimise the environmental impacts of acid mine drainage and other issues are outlined in this report, highlighting the need to correctly characterise all waste rock produced during mining in order to properly manage the material in the long term.

Chapter 3 addresses aspects of leading uranium mining operations that have been introduced as regulations and practices evolved in response to the evolution of societal attitudes about health and safety and environmental protection. Such aspects of mine management were seldom, if ever, followed in the early stages of uranium mining. **Public participation** is one such aspect and must be an integral part of planning and approval processes for uranium mining, along with transparency and assurances of performance throughout the entire life cycle of the facility. Today, leading practice uranium mining includes repeated opportunities for public consultation throughout the life of a mining facility.

Past experience with environmental legacies has also underlined the need to plan projects carefully through an **environmental impact assessment** process with opportunities for stakeholder participation, which includes the interested public and special interest groups, such as indigenous peoples. In order to demonstrate that facilities are performing as designed, the collection of baseline environmental data to objectively assess ecosystem impacts throughout the life of the mine with **environmental monitoring** programmes is essential to provide assurance of performance.

The mining industry generates significant economic opportunities during mine development and production, but can ultimately leave a gap in the regional economic infrastructure when operations are closed. In order to evaluate the impacts on the local community, an analysis of **socio-economic impacts and benefits** is undertaken in leading practice jurisdictions prior to decisions to begin mining. If mining is approved, arrangements are typically established to ensure that local inhabitants benefit from the extraction of the resource, even after the mine closes, since businesses and skills developed during operations are transferable to regional mining and other activities.

Past uranium mining legacies from the early strategic production era have been left to governments to remediate, often at a high cost. To ensure that the mining companies, not governments, are responsible for funding decommissioning and remediation activities, leading practice jurisdictions require uranium mining companies to post **financial assurance** to cover the costs of closure and remediation activities should the company not be able to meet its commitments. In essence, this means that mining companies must produce an acceptable closure and remediation plan approved by the regulatory authorities prior to beginning mine development, and post appropriate financial guarantees for the expected cost of implementing the plan once mining is completed.

Because of the radioactivity of uranium deposits and the strategic importance of uranium, governments and operators are also required to put in place **emergency planning** measures to deal with on-site accidents, to secure safe **product transport** and to adhere to international **security and safeguard** requirements. These aspects of leading practice uranium mining are outlined to illustrate the commitment made by modern uranium mining companies to effectively prepare for emergencies and ensure safe product transport.

The final stage of a mine's life cycle is to return the land to the landowner following completion of mining closure and remediation activities. Once the results of environmental monitoring have shown that the remediated facility is performing as designed, mining companies can proceed to this handover stage. To ensure the proper long-term

management of land used for mining, a systematic means of **knowledge transfer** designed to preserve important records relevant to the facility and its proper maintenance is required so as to ensure that future generations have the information necessary to properly intervene at the site, should the facility cease to perform as required.

Experiences from modern uranium mines show that in countries with the appropriate regulatory requirements and a regulatory agency staffed with qualified personnel, successful companies develop innovative strategies to manage all potential impacts of mining and processing on workers, communities and the environment. An ongoing dialogue among the main stakeholders – the community, the mining company and the government – has proven critical in this regard. With the participation of the main stakeholders, and with companies setting aside adequate funding for site remediation, public funding for uranium mine site legacies and remediation should no longer be required. In effect, these measures help to ensure that no additional legacy uranium mining and milling issues will be created and left to governments to remediate.

Concluding remarks in Chapter 4 underscore that modern uranium mining is highly regulated and in several important ways distinctly unlike mining practices employed in the past. Today, mine and mill workers are trained and protected from unacceptably high exposure to radiation through a combination of implementing safe working practices and, in both underground mining operations and uranium mills, using high-capacity ventilation systems that continuously evacuate airborne radioactive particles from higher-risk working areas. Environmental planning and monitoring throughout the life cycle of the mine ensures that the planned life cycle performance is achieved through to the post-decommissioning period, minimising the environmental effects to acceptable standards and avoiding impacts on local populations. These greatly improved modern mining practices are the combined result of learning from past practices, the implementation of stringent regulatory requirements to achieve societal expectations and the successful application of innovative approaches developed by companies to meet, and in many cases exceed, these regulatory requirements.

The need to fuel existing and future NPPs worldwide will translate into a demand for uranium in the decades to come. New uranium mining operations will likely be initiated in countries that, in some cases, have never hosted uranium mining. The important role that stakeholders play in such cases is paramount to make certain that leading practices become normal practices so as to facilitate the safe development, operation and closure of uranium mining operations, and thus ensure that a positive legacy will be left for future generations. This report has been produced to assist in this transition and to help pave the way for broader public acceptance of this important but sometimes poorly understood industry. The goal of this report is to outline how leading practice uranium mining is conducted. A detailed review of each mining operation around the world is beyond the scope of the report. Moreover, publicly available documents of the required detail were not available for every producing country, making it impossible to assess all currently operating uranium mines. Case studies from leading practice operations in Australia, Canada, Kazakhstan and the United States were chosen under the guidance of ad hoc expert group members where pertinent, publically available documents produced by governments, regulatory agencies and uranium mining companies were available.

In addition to providing an updated overview of leading practice uranium production for the interested public, recommendations on regulation and mine development policies for currently producing countries and for those countries that are considering hosting uranium production for the first time are provided. It is recommended that producers should be open and transparent about their operations and that those purchasing uranium should preferentially buy from countries with an acceptable regulatory system that covers key aspects of the mine life cycle and from producers that meet minimum leading practice requirements. Doing so will help ensure that leading practice becomes common practice.

Chapter 1. Introduction and overview

"I'm dismayed that recent statements and discussions over the safety of uranium mining have been based neither on fact nor science … claims that the public and environment are at risk are fundamentally wrong … [regulatory] conclusions on the uranium mining industry are clearly based on decades of studies, research, and a rigorous licensing and inspection framework" (Canadian Nuclear Safety Commission President, Mr M. Binder [open letter, 22 November 2011]).

Purpose

The purpose of this publication is to provide an overview of leading practice uranium mining operations and to contrast them with past practices that created environmental and health legacies. Today, modern uranium mining operations successfully manage environmental and health impacts and have developed into arguably one of the safest and most environmentally responsible forms of mining in the world.

This report aims to be a readable, non-technical outline of leading mining practices and the regulatory environment in which it is undertaken. The considerable evolution of regulations and uranium mining practices that has occurred over the last few decades is summarised to show how issues that arose from uranium mining during the early phase of the industry decades ago are being successfully managed today.

Safe and environmentally low-impact uranium mining is not just a matter of interest to uranium producing companies and countries; it is also of concern to those using the product to generate significant quantities of baseload electricity at nuclear power plants (NPPs) with low CO_2 emissions and to those benefitting from the low-cost electricity produced. Given the long lifespan of the over 430 operational facilities today and the growing number of countries with either NPPs or plans to construct them that have no domestic uranium mining, the issue of sourcing uranium from countries with an acceptable regulatory framework and mining companies applying leading mining practices is becoming increasingly important.

In Chapter 2 (operational challenges), mining practices today are compared and contrasted with those used during the period in which uranium mine legacies, environmental issues and health impacts were created. A common structure is used to illustrate how the management of the most significant aspects of the uranium production life cycle (i.e. worker and public health and safety, water quality, tailings and waste rock management) have evolved. Case studies are presented to contrast past practices with current practices in order to outline the degree of change and to demonstrate how each aspect is being successfully managed today.

Chapter 3 (modern life cycle parameters) outlines aspects of modern uranium mining that were seldom, if ever, followed in the early stages of uranium mining when legacy wastes were created and the health of miners and local residents was negatively affected. The application of these new, additional aspects of full life cycle mine management, such as public consultation, the collection of baseline environmental data, environmental impact assessment (EIA) and environmental monitoring, an evaluation of socio-economic impacts and benefits, financial assurance, emergency preparedness, product transport,

security and safeguards and knowledge transfer during decommissioning, are critical to the successful management of health and environmental issues throughout the full life cycle of a mine.

The range of operational aspects and leading practices described explain how organisations employing these practices operate one of the safest and most environmentally responsible forms of mining in the world. This is important since uranium requirements are expected to grow in the coming years and new mines will need to be brought into production.

Nuclear power and uranium requirements

Nuclear power offers a number of economic and environmental benefits that underpin the deployment of NPPs in 30 countries around the world today. The electricity generated is competitively priced (NEA, 2010a), taking into consideration the entire life cycle of the generating facilities, providing base load power to electricity grids, regardless of weather conditions.

With high upfront costs for licensing and building NPPs, the most economically efficient mode of operation is running continuously at high capacity as is safely and technologically feasible (an operation lifetime of 60 years has been licensed in many NPPs in the United States). Electricity generated at NPPs is free of CO_2 and other greenhouse gas emissions at the point of generation. The technology is also one of the safest forms of electricity production, compared to other generation technologies) in terms of health impacts on workers and local residents (NEA, 2010b), although two severe nuclear accidents (Chernobyl and Fukushima Daiichi) have shown that consequential impacts can be widespread, disruptive and costly.

Wide ranging sources of uranium for the production of compact and easily stored nuclear fuel provides countries with a fleet of NPPs enhanced security of energy supply. Uranium and manufactured fuel bundles account for only about 15% of the operating costs of an NPP, compared to natural gas and coal where fuel accounts for 60% or more (IEA, 2012). Fuel price changes clearly do not affect NPP operating costs to the same degree as generators burning fossil fuels.

There are also environmental benefits. Nuclear energy plays an important role in limiting greenhouse gas emissions in the power sector. In 2010 (IEA, 2012), nuclear represented 12.9% of the world electricity production, the second largest low-carbon source behind hydro (16.1%). In OECD (Organisation for Economic Co-operation and Development) countries, nuclear energy is the largest source of low-carbon electricity, with a share of 18.9% of total electricity production in 2012 (NEA, 2013), despite the closure of all but two reactors in Japan following the Fukushima Daiichi accident. When the entire life cycle of uranium is considered (from mining through generation to disposal), greenhouse gas emissions per kilowatt-hour of electricity generated are as low as renewable energy sources (NEA, 2012).

There have been claims that life cycle emissions of the nuclear fuel cycle are much higher, depending mainly on assumptions made about emissions arising from mining and enriching uranium in the fuel production process. Recent analysis (NEA, 2012) shows that at a uranium ore grade as low as 0.01%, nuclear power clearly belongs to the low-carbon technologies of today, even in a society dominated by fossil fuel electricity generation. In the case of an extremely low ore grade of 0.001% and fossil-based electricity use for extraction and processing, the nuclear fuel cycle would emit one order of magnitude lower CO_2 emissions than coal power. As society moves towards a low CO_2 or CO_2-neutral energy economy, the indirect (fuel cycle) emissions of nuclear power generation will gradually diminish, as will be the case for most renewable energy conversion technologies.

With 437 reactors operational worldwide at the end of 2012, over 60 under construction and several tens more under consideration, providing fuel for these long lifetime facilities is necessary to ensure an uninterrupted supply of baseload electricity. With the capacity of the global nuclear fleet expected to continue to increase in coming years, despite the phase-out plans announced by a few countries following the accident at the Fukushima Daiichi NPP in Japan, there is a need to maintain output at existing production facilities and ultimately increase uranium mine production.

Uranium supply

A key part of the history of uranium mining began in the 1940s when military requirements produced the first peak in production. When these requirements were met, the industry went into decline until expectations of significant additions of civil nuclear generating capacity sparked another surge in production (Figure 1.1). The uranium produced during these two periods of intense activity was greater than required, producing an inventory of material that continues to supply a portion of market requirements even today.

For at least the past two decades, reactor fuel requirements have been met by a combination of freshly mined uranium (primary supply, roughly 70% to 85% of demand) and previously mined uranium (secondary supply, roughly 15% to 30% of demand). An important source of secondary supply has been the 20-year agreement between the United States and the Russian Federation to blend down weapons-grade highly enriched uranium (HEU) to low-enriched uranium (LEU) suitable for nuclear fuel. This agreement ended in 2013, reducing annual secondary supply by the equivalent of some 9 200 tU (tonnes of uranium metal). Other sources of secondary supply include reprocessed and recycled spent fuel and uranium tails at enrichment plants that can be run through the enrichment process again (re-enriched) to produce LEU, with the right market conditions.

Nuclear reactor construction is proceeding in some countries, ambitious expansion plans have been announced in others and several, particularly in the developing world, are considering introducing nuclear power to meet rapidly rising electricity demand. Although a few countries have recently decided to either withdraw from the use of nuclear power or not proceed with development plans following the March 2011 accident at the Fukushima Daiichi NPP in Japan, prospects for growth in nuclear generating capacity remain positive. Despite this serious, high-profile accident, long-term projections of nuclear power capacity show that prospects for growth have not been greatly affected, perhaps declining by some 15% to 20% compared to projections prepared prior to the accident. Even if such a large degree of projected growth in nuclear generating capacity is not realised, any growth in nuclear power generation capacity will lead to increased uranium supply requirements.

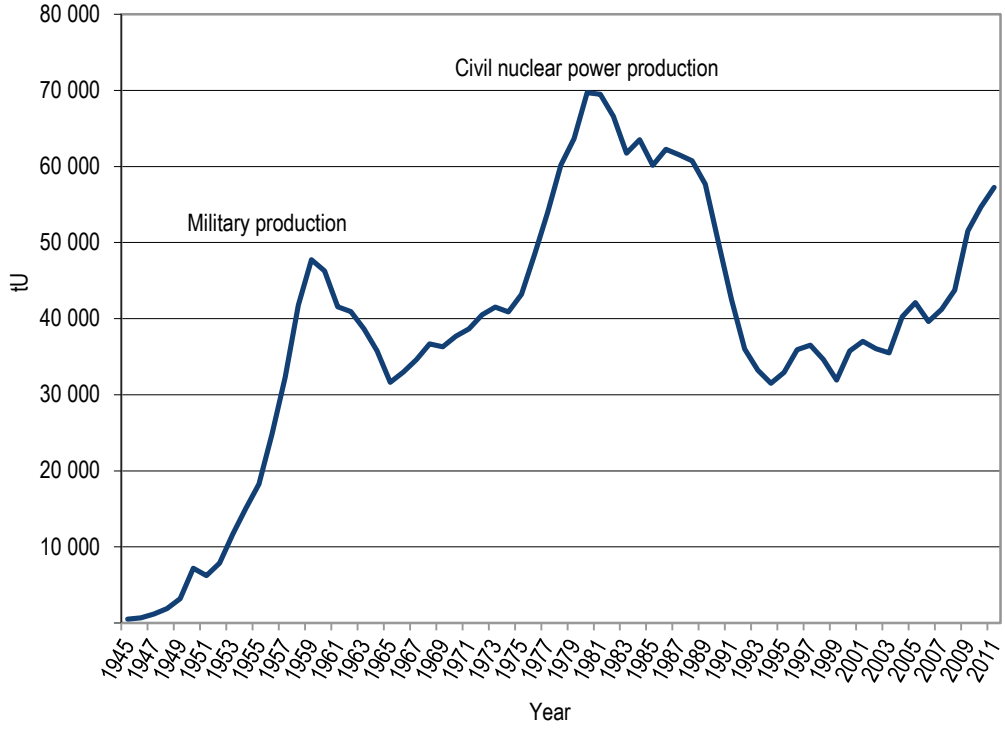
Recent increases in global uranium mine output have been driven mainly by rapidly increasing production in Kazakhstan. However, it is unlikely that Kazakhstan can sustain this rate of growth. Moreover, existing mines around the world have a definite life span and some are nearing the end of their operational life span. New mines are under development but take time, expertise and resources to be brought into production.

General overall increases in the uranium market price since 2003, despite declines since 2007 and following the Fukushima Daiichi accident, have driven a great deal of exploration and mine development activity. However, uranium producers outside Kazakhstan have thus far been hard pressed to increase primary production. Stringent regulatory requirements for mine opening, combined with technical challenges, the ongoing financial crisis, uncertainties related to nuclear power development and, in turn, near-term uranium requirements, have made the process of raising investment and opening new mines particularly long (ten years or more) in mature regulatory regimes

such as those in Australia, Canada, the United States and elsewhere. Public resistance to uranium mining has at times slowed mine development in these and other countries.

Given requirements to fuel the existing fleet of NPPs for decades to come, projections of increasing uranium demand and declining secondary supplies, expansion of existing uranium mines and development of new mines will be needed in countries where public perception of uranium mining could potentially be improved with a better understanding of leading practice mining operations. This report has been developed to inform and assist in the development of leading practice uranium mines to meet rising demand.

Figure 1.1. World uranium mine production 1945-2011 (adapted from NEA/IAEA, 2012)



Past and present uranium mining practices

Public perception of uranium mining is largely based on the adverse health and environmental impacts of past practices that took place during a largely unregulated early phase of the industry. During the Cold War and the initial stages of the development of civilian nuclear power, uranium mining was conducted mainly by governments (or companies under government contract) for strategic military purposes. The driving force of the era was maximising production, with little regard for environmental consequences. Societal expectations of heavy industry were similarly focused on economics. The concepts of sustainable development and environmental stewardship had not yet been expressed or embraced. Legacy mining facilities in countries in which uranium mining was conducted in this early era, such as Australia, Canada, the Czech Republic, Estonia, Hungary, Kazakhstan, Kyrgyzstan, Poland, Romania, the Russian Federation, Slovenia, Ukraine, the United States and Uzbekistan rely on governments to finance the clean-up required to render the sites safe and stable. Although many of these legacy facilities have been remediated, the effort expended and work that remains to be done serves as a reminder of the impacts of past uranium mining practices.

Worker health and safety awareness and associated regulations were also in their infancy during this early stage of uranium mining. The result was that workers were being exposed to levels of radiation considered hazardous today and an increased incidence of lung cancer was documented. The health of residents in the vicinity of early uranium mining facilities was also negatively affected since uncontained tailings and untreated discharges contaminated local drinking water supplies.

In contrast, modern uranium mining is highly regulated and, although looking similar to past operations to the casual observer, is in several important ways distinctly unlike mining practices employed in the past. Today, mine and mill workers are trained in safe working practices and are protected from unacceptably high exposures of radiation through a combination of working practices and design and engineering measures, such as high-capacity ventilation systems that continuously evacuate airborne radioactive particles from high-risk working areas, notably in UG mining operations and in uranium processing plants (mills). Worker exposure to radiation is monitored on the job to ensure that exposures are maintained well below internationally accepted limits and as low as reasonably achievable, social and economic factors taken into account (the ALARA principle). Environmental planning and monitoring throughout the life of the mine provides assurance that planned life cycle performance is achieved right through to the post-decommissioning period, minimising environmental impacts to acceptable standards. These greatly improved modern mining practices are the combined result of learning from past practices, implementing stringent regulatory requirements to meet societal expectations and applying innovative approaches developed by companies to meet these requirements.

To ensure that no new legacy wastes and sites are created, leading practice regulatory authorities require that mining companies develop acceptable mine closure and remediation plans and provide financial guarantees for the orderly closure and remediation of the mine **before** issuing a licence to begin mining. Periodic review of these plans and guarantees allows amounts to be adjusted as operations develop in size and complexity or as progressive decommissioning is achieved. As a result of these above mentioned measures in operation and licensing, uranium mining facilities in operation today typically have generally strong support from local residents.

Historical development of mining regulation and licensing

The history of uranium mine regulation is closely related to the general history of mining and societal expectations that drove its development. The reasons why historical uranium mines, even into the late 1970s in some cases, were allowed to operate in the manner that left a legacy of contamination and impacted worker health and safety is an important aspect of the history of uranium mining.

The significant historical periods can be summarised as follows:

- the first uranium minerals recovered in the early 1500s while mining for silver in the Ore Mountains between what is today Germany and the Czech Republic;
- radium and uranium recovery for medical purposes and research (1895-1920s);
- uranium mining for military purposes (1940s);
- uranium mining for military and early nuclear research/power requirements (1947 to mid-1960s);
- uranium mining primarily for civilian nuclear power and research reactors, prior to effective worker and environmental protection and controls (mid-1960s to 1970s);

- the establishment of modern uranium mining facilities with evolving, improving regulatory requirements (1980s to present).

Uranium was first separated from the mineral pitchblende while mining for silver in St. Joachimsthal (Jáchymov) in 1789. Miners soon became aware of the unique properties of this black mineral and some also came down with a mysterious illness after working with it. By the mid-1800s, pitchblende was valued because it gave glass a brilliant yellow colour and green fluorescence. In 1895, the radioactive properties of uranium were confirmed, stimulating further research, particularly in the medical field. Interest in uranium intensified during World War II as the discovery of the power of its fission properties became of interest to the military.

The early history (from discovery to World War II) occurred in what can be broadly termed a "free mining" system (Barton, 1993). With origins dating as far back as ancient Greece and medieval Europe, regulatory oversight to protect people and the environment was virtually non-existent in free mining systems. Although regional variations exist (e.g. in Germany and most of continental Europe, where regional rulers developed laws governing the mining of precious minerals that led to the establishment of mining regulations in the 19th century), in essence free mining allowed mineral resources to be accessed with few constraints in a given territory or on publicly owned lands.

This historical approach carried over to the early mining laws of countries that were at one time European colonies, including Australia, Canada and the United States. The impacts of this free mining approach are evident in the gold rushes of 1840s to 1890s across North America and Australia, where staking and gold mining took place with virtually no regulatory oversight for environmental protection or worker health and safety. As a result, governments even today continue to address the effects of these largely unregulated practices that produced legacy mines around the world. These operations were sited, operated and abandoned with little to no attention or foresight given to impacts on the workers, the local population or the environment.

After World War II during the ensuing "Cold War", uranium mining activities expanded rapidly around the globe as the stockpiling of nuclear weapons and fission material increased. As a highly prized "strategic material", uranium became shrouded in secrecy under "rights of the crown". Worker health and safety as well as environmental protection were not on the list of priorities.

By the 1970s, escalating impacts from the operations on the health of workers, the environment and the communities located nearby became increasingly evident. Societal pressure, typically driven by unions representing miners, led to a number of investigation boards, commissions of inquiry and numerous health studies that clearly identified the extent and far reaching impact of historic mining operations that lacked proper operational and waste management practices. These impacts were common to all metal mines, but exacerbated for uranium mines due to the added hazard of radioactivity. The radioactive wastes arising from uranium mining and milling were, in some cases, significant. The measured impacts to worker's health and increasing cases of lung cancer required government and regulatory action.

It is out of the inquiries, special commissions and focused investigations and research in the 1960s and 1970s that modern mining and milling practices were born (e.g. Ontario, 1976). Moving from virtually no waste management planning (i.e. the discharge of untreated mine and mill wastes into conveniently located low-lying areas, lakes or streams) to multistage effluent treatment processes with engineered, purpose-built waste management systems of today, was an arduous process based on lessons learned spanning more than three decades. In terms of worker protection, the mining industry was transformed from one in which miners were working in poorly ventilated UG mines with minimal training and ground support, to one with a geotechnical and structurally designed, well-ventilated and monitored mine working environment with well-trained staff, qualified mine engineers and dedicated safety supervisors to monitor and oversee

the operations. Both of these areas of improvement were equally challenging and involved the emergence of stronger regulatory/government oversight and inspections. This also resulted in increasing consequences for poor performance or non-compliance through the force of law.

The timing and expectations of uranium mining in a number of countries through the 1940s to the 1980s was marked by a variety of experiences and lessons learned that led to the development of modern regulatory regimes at different paces. For example, legacy mining and milling practises continued until as late as 1990 in the USSR and its allied countries in Central Asia and Eastern Europe.

In North America, federal or national regulations relevant to mining and environmental impact pertained primarily to mine effluent quality and its potential impact on fish and downstream water uses. Regulations specifying procedures for monitoring water quality, setting discharge criteria and defining permissible impacts are generally administered by provincial or state authorities, each with its own laws and regulations governing EIAs and requirements for mine operation and closure criteria.

The European Union (EU), through a combination of environmental, health and safety and human rights laws, specifies the proper management of mines and mining wastes. These rights and charters bind EU member states and its institutions, guaranteeing the overall protection of certain human rights that could be impaired by mining activities. Uranium mining regimes in Australia and South Africa have followed similar protocols to improve regulatory oversight and control.

In terms of the countries that are further developing their uranium resources, such as Kazakhstan, legislation and laws on nuclear energy use and radiation safety brought into force in 1997 and 1998 have been further modernised since 2007. In Namibia, the process of updating laws and regulations is taking place as the uranium industry grows. The Atomic Energy and Radiation Protection Act was passed in 2005 and regulations to operationalise the act came into force on 16 January 2012.

Today's leading practice regulators for uranium mine and mill sites, and other types of nuclear facilities, are regulated by an independent agency that reports to the head of state or parliament and its elected officials. This reduces the possibility that political or economic goals could influence regulatory decisions. The nuclear regulatory agency ideally operates under a judicial or quasi-judicial process, making decisions in an open and transparent manner, maintaining a clear record and allowing anyone the right to be heard.

The priorities of a nuclear regulatory agency are the safety and security of radioactive materials and nuclear facilities, the health of the public and workers as well as protection of the environment. Regulatory powers are invoked through an act of government (or parliament) and are further detailed in supporting regulations to the act, licences issued in accordance with the regulations and their supporting regulatory and guidance documents.

A leading practice nuclear regulatory agency uses a comprehensive licensing system that covers the entire life cycle of a facility from site preparation and construction, through operation to decommissioning/remediation and release from licensing (i.e. from cradle to grave), using a stepwise and integrated approach. For uranium mines and mills some form of institutional control or end state maintenance and monitoring programme is normally required when the decommissioned site is returned to the government. This will be undertaken by a regional agency (provincial or state) or national programme in order to ensure that the safely decommissioned site is not disturbed and its performance meets the long-term objectives.

Every new mine project will be assessed for potential environmental impacts, usually in accordance with an independent national or regional environmental assessment act or regulation. The outcome of the environmental assessment and licensing process feeds

into a regulatory compliance programme used to verify that the licensee is fulfilling all regulatory requirements. These agencies need to be staffed by properly trained personnel to carry out the necessary assessments, inspections and enforcement backed by the force of law.

To expedite regulatory reviews and public consultations, proponents should submit very early on in the application process all the relevant information required in the regulations and associated with the site operation and the decommissioning plans. This information must be made available to all stakeholders, including the public. Financial guarantees to cover all costs associated with the safe shutdown, monitoring, maintenance and decommissioning of the facility are also required for all the life cycle stages, including the release from formal licensing to institutional controls. Regulatory costs to conduct technical assessments, perform routine inspections and detailed audits, plus administrative costs during operations can all be recovered under some form of regulatory fee recovery system. This ensures the public or tax payer is not funding this level of regulatory effort, and the national nuclear regulator in countries like the United States and Canada utilise such a system.

Experiences from modern uranium mines show that successful companies have developed strategies to handle the positive and negative impacts of mining and processing on communities and the environment. This has occurred with the close co-operation, communication and participation of neighbouring communities. A dialogue must take place among the community, the company and the government, with the end goal of ensuring that no additional legacy mining and milling sites, health or environmental issues are created. With careful execution and participation of the these three main stakeholders, and adequate funding set aside for site remediation by the companies, public funding for uranium mine site remediation should no longer be required.

Developing, staffing and maintaining a leading practice mine regulator takes time and resources. Countries beginning uranium mining for the first time have the opportunity to benefit from past experience in other countries, but will generally require time to develop the capacity and regulatory framework required to nurture leading practice mining. Considering that the final design and construction of a new mine can take up to ten years, there is time for the development of a modern regulatory framework, including inspection protocols.

Mining types and life cycle operational phases

There are a wide range of parameters that must be considered in all stages of mining and processing to effectively manage health, safety and environmental protection. In this document the main mining types are the focus: *in situ* leach (ISL), open-cut (OP) and underground mining (UG). There are a number of other ways to produce uranium, including recovery as a by-product (e.g. in mines where copper or gold is the primary product), water or effluent treatment and re-treatment of mine tailings or other waste streams – but in these cases the ore has already been mined and the management of impacts will be addressed under the main mining types. In the case of water or effluent treatment and recovery from tailings or other waste streams, reducing environmental impacts is the main goal of the activity.

There are numerous ways of extracting the uranium from the ore, a process conducted at a nearby facility known as a mill, the most common being acid or alkali vessel leaching (under either atmospheric or pressurised conditions), followed by solvent extraction or ion exchange and subsequent calcinations for the production of uranium oxide or concentrate (UOC), commonly referred to as “yellow cake”.

ISL operations (sometimes referred to as *in situ* recovery, or ISR) extract uranium from the host rock without the need to excavate and mill the ore. Generally, ISL consists of

injecting a leaching solution via injection wells into the mineralised aquifer and recovering the mobilised uranium from solutions pumped to the surface. ISL operations are generally characterised by very low surface impact and disturbance and the critical environmental consideration is almost exclusively the impact of the activity on groundwater.

Open-pit mining (sometimes referred to as open-cast or open-cut mining) involves extracting the ore directly by removing overburden to directly access the ore. This is most commonly used for ore bodies which are either on surface or relatively near surface. As depth to the deposit increases, the size and cost of the operation will increase as will the amount of waste rock generated. OP operations are characterised by a high ratio between waste rock and ore and hence have the largest surface impact.

Underground mining is generally used for more deeply buried deposits or where the ore is distributed in such a way that high-grade zones can be mined preferentially (i.e. vein type deposits). UG mining is typically the most expensive form of mining per tonne of rock and has historically been regarded as the highest risk due to potential rock falls and underground collapses. It often has a low ratio of waste rock to ore and in some UG mines there is no significant generation of waste rock. Therefore the surface signature from an UG mine is relatively small.

In this report the life cycle operational phases are considered to begin once exploration has been successful in defining an ore body of commercial interest. The subsequent phases are:

- **Design** covers all aspects of developing an ore body from discovery to mine production. This includes conceptualisation, pre-feasibility, feasibility, design, environmental assessment, detailed design and preparation for construction itself. This phase is necessary in order to document all potentially significant impacts, obtain regulatory approvals and develop corresponding corrective actions.
- **Construction** includes all physical activities on-site to prepare the area for construction, mobilise workers and materials to the site and the undertaking of all the physical construction work as determined by the detailed design. Quality controls, field modifications and staged commissioning of the newly constructed infrastructure are components of the construction phase. This phase literally lays the groundwork for how safely the facility can operate during the production phase.
- **Production** includes all aspects of the operation while production is still the primary purpose, including temporary production suspensions, care and maintenance and expansion activities. This phase is where most of the immediate impacts will occur and, in turn, where active controls dominate.
- **Rehabilitation** covers all activities from the end of production to the final handover to the authorities, including closure of the operation, physical decommissioning and remediation activities, as well as monitoring and surveillance required to confirm that the rehabilitated site is performing as designed. Although aspects of rehabilitation can be undertaken during the production phase, all remaining decommissioning and remediation activities are completed during rehabilitation. Moving from active controls to passive controls is the dominate activity in this stage.
- **Handover** is the period when formal control is transferred from the mining company to the authorities. Acceptance of the rehabilitated facilities can be a significant risk to the authorities, so there is a need for rigorous requirements and the need to demonstrate that the facility is capable of long-term compliance. In the setting of handover criteria, sometimes referred to as **institutional controls**, the onus is on government authorities to ensure that long-term health, safety and environmental protection is in place, is well funded and sustainable.

Operational challenges

For each individual operation there is a wide range of issues that must be addressed when managing health, safety and environmental risks. These operational challenges are divided into key historical ones (1 through 5) and modern life cycle parameters (6 to 14):

1. **Worker health and safety** is a critical component of leading practice mining operations. Although reducing *radiation exposure* is a key aspect of health management for all operations, UG operations generally have the greatest potential for higher exposures. Higher potential exposures are also associated with some stages of processing, such as during handling of UOC and during other process steps, for example by-product smelting and release of volatile polonium (^{210}Po), scale build-up and exposure to radium (^{226}Ra) and decay products. *Conventional worker health and safety* is of importance throughout all phases of an operation. UG operations have some inherently higher risks and as such require specific controls to manage potential impacts.
2. **Public health and safety** issues are focused on nearby populations and whether there are potential direct pathways by which the public may be exposed. Generally, open-cut operations have the highest emission characteristics and quantities and require more controls. During rehabilitation and handover, public dose increases in importance as restrictions are reduced or removed on direct public access to disturbed mine areas and tailings facilities.
3. **Water quality** issues are critical to managing the environmental impact of a mining facility, given the need for the proper treatment and disposition of surface and groundwater affected by operational use. This is often more important for open-cut mines due to the size of the catchment area affected and the potential need for water to control dust. *Surface water* requirements will be driven by the local surface hydrology. *Groundwater* protection requirements are generally dominated by the site-specific hydrogeological nature of the operational area and are of particular importance in ISL operations.
4. **Tailings** are one of the most significant operational and long-term hazards for conventional processing (milling) operations that can lead to serious impacts if not properly managed. Tailings retain the majority of the radioactivity of the ore (most of the uranium is removed, but radioactive daughter products remain in the tailings) and they may be more susceptible to liberating radionuclides or other hazardous materials (such as heavy metals) to the environment. Tailings management in the very long term broadly encompasses the chemical and physical processes involved in the production and placement of tailings, as well as the development, operation and closure of the facility into which the tailings are impounded to isolate and minimise, through controls, the release of hazardous materials. Long-term rehabilitation of tailings facilities is often a critical component of the closure and handover of an operation.
5. **Waste rock** can be a major issue, particularly in OP mines, due to both radiological and non-radiological properties. For example, the generation of acid rock drainage from oxidised sulphate-rich waste rock and the liberation of other contaminants as carbonate-rich waste rock is acidified can, if not properly managed, result in significant environmental impacts. Alternatively, waste rock without these properties can be a resource, both for the construction of facilities for the operational phase and as an economically available cover material for rehabilitation, or other external uses.
6. **Public consultation** is critical throughout the entire mine life cycle. Uranium mining is often contentious and public consultation is required for both legal and community reasons (i.e. obtaining and maintaining a social licence to mine).

Generally the most important phases for public consultation are during design (particularly EIA), early operation and rehabilitation, but continuous contact with stakeholders has proven to be an effective way of demystifying the operations and minimising unjustified resistance to the activity.

7. **Environmental impact assessment (EIA)** is a process used to predict and minimise environmental effects of proposed initiatives before they are fully planned and undertaken. It is a critical step in mine development. An EIA defines all possible relevant environmental, social and economic impacts (both positive and negative) of a proposed project. It should provide all stakeholders with an opportunity to review a comprehensive evaluation of the project and provides decision makers with all the information required to make decisions concerning project development and the conditions under which it may proceed. **Baseline environmental data** collected in preparation for the environmental assessment stage and provided to regulators is essential data used throughout the life of the facility in order to gauge performance of the facility and its surroundings during operations, rehabilitation and handover.

8. **Socio-economic impacts/benefits** need to be carefully considered in the EIA since mine development can have both positive social and economic benefits through job creation, taxes and royalty payments to governments. It can also have negative impacts, such as the effects of industrial activities on existing lifestyles, the possible influx of outsiders and the eventual closure of the mine (mines can run for decades, but not forever), particularly when a local economy is built up around employment and support activities during mining operations.

9. **Environmental monitoring** is an essential safety and environmental protection function of any mining facility. Comprehensive environmental monitoring throughout the life cycle of a mine facility is essential to demonstrate that the facility is performing as predicted and that environmental impacts are not exceeding acceptable levels, as benchmarked by *baseline environmental data* and following national or international guidelines and regulation.

10. **Financial assurance** is critical throughout the life of the mine, but particularly so during the rehabilitation and hand over phases. Historically, there have been cases where funding was insufficient for these final life-cycle phases and governments were required to fund the management of residual risks and impacts, including remediation costs. During handover there may need to be some economic provision to ensure that the long-term safety of the facility is maintained into the future.

11. **Product transport** protocols are required since the transportation of various hazardous materials during construction and operation (e.g. acid, fuel, reagents or explosives) as well as the final or interim product, like UOC or uranium-containing resin is a necessary part of all operations. Due to the expanded development of mining operations in various locations and the long-term imbalance between uranium producing and consuming countries, safe transportation practices have been and continue to be important to the industry.

12. **Emergency planning**, encompassing both emergency preparedness and emergency planning, is a part of all mining operations because hazardous operating materials (like aggressive chemicals or explosives) are regularly used. For uranium mines and mills, radiological hazards also have to be considered, although no off-site consequences resulting in serious radiological exposure are expected from these operations. The level of emergency preparedness is generally highest during operation and special attention is required for UG operations due to the inherent difficulties involved in any underground emergency.

13. **Security and safeguards** have gained importance in recent years, especially after the events of September 2001 in New York. Although the establishment and maintenance of a good physical protection regime lies in the hands of the state, it is the responsibility of the operators to adopt and implement security measures on-site and during transport according to national and international nuclear security requirements. It is important that responsibilities are clearly assigned to operators and carriers and that periodic evaluation and improvements in security measures are undertaken.
14. **Knowledge transfer** is essential for the long-term stewardship of decommissioned and rehabilitated facilities. A system to archive key data on the inventory of hazardous materials and the status of the reclaimed areas and remediated waste objects, environmental monitoring data and predictions regarding the long-term performance, as well as the supporting documentation is essential.

Examples of successful approaches and case studies for managing health and environmental impacts are provided in this report and it is important to note that the approach taken to meet current expectations for uranium mining is highly dependent on **site-specific factors**. Underlying principles to successful management remain the same, but the method of application can vary from operation to operation, depending on local circumstances. Any approach taken must be tailored to the individual operation and generic approaches are very rarely appropriate. However, where significant improvements in performance have been realised, the successful approaches may be applicable to operations elsewhere.

Table 1.1 summarises the relative importance of each of the above-mentioned aspects of the full life cycle of a uranium mine.

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Table 1.1. Relative importance of operational aspects and modern life cycle parameters for types and phases of uranium mining

Aspects	Exploration	Design			Production			Rehabilitation			Hand over		
		ISL	Open-cut	UG	ISL	Open-cut	UG	ISL	Open-cut	UG	ISL	Open-cut	UG
Operational													
Worker H & S (radiation)	**	**	***	****	**	***	*****	*	**	***	n/a	n/a	n/a
(conventional)	****	***	***	****	****	****	*****	***	***	***	n/a	n/a	n/a
Public safety (radiation)	*	*	***	***	**	***	**	*	*****	****	***	****	****
Water/quality (surface)	**	**	****	***	**	****	**	**	****	***	*	****	***
(groundwater)	*	*****	***	****	*****	***	***	*****	***	***	****	***	***
Tailings	n/a	n/a	****	****	n/a	****	****	n/a	****	****	n/a	*****	*****
Waste rock	***	*	****	**	*	****	***	*	*****	***	n/a	****	**
Leading practice processes													
Public consultation	**	***	****	****	***	***	***	****	****	****	**	**	**
Baseline environmental data	*	*****	*****	*****	**	**	**	**	**	**	**	**	**
Environmental impact assessment	*	*****	*****	*****	***	***	***	***	****	****	**	***	***
Socio-economic impacts/benefits	**	***	***	***	****	****	****	***	**	***	**	**	**
Environmental monitoring	*	*****	*****	*****	*****	*****	*****	****	****	****	***	***	***
Financial assurance	**	***	****	****	*****	*****	*****	****	****	****	*****	*****	*****
Product transport	***	*	*	*	****	****	****	*	*	*	n/a	n/a	n/a
Emergency preparedness	*	*	**	****	***	***	*****	**	**	**	*	****	***
Security and safeguards	*	**	**	**	***	***	***	*	*	*	n/a	n/a	n/a
Knowledge transfer	**	**	**	**	**	**	**	***	***	***	****	****	****

n/a = Not applicable; * Very low importance; ** Low importance; *** Normal importance; **** High importance; ***** Critical importance.

Chapter 2. A Comparison of key operational challenges

Although the regulatory environment within which uranium mines operate today and the way in which environmental and health issues are managed have changed considerably since the time that legacy mines were created, many of the same operational challenges must be addressed by uranium producers. Since early management practices of these aspects of operations led to the most significant issues arising from legacy facilities, the way in which these key operational challenges are managed today is compared with the way in which they were managed in the past. Case studies outlining historic management practices, current leading practice and the outcomes of the two different approaches are presented to illustrate the differences between the old and new modes of operation.

2.1. Worker health and safety

The health and safety of the workers and the public are crucial components of leading practice mining operations. Historically however, the health and safety of workers and the public was neither well understood nor the high priority issue that it is today. This important topic will be addressed below dealing with mine and mill workers first, then the public. For mine and mill workers, conventional health and safety issues will first be discussed, followed by worker radiation protection.

Conventional (non-radiological) worker health and safety

All mining activities have long been perceived as hazardous and high risk. Due to the inherent nature of mining, involving the use of heavy equipment, large transfers of materials, hazardous chemicals, work in potentially hazardous environments often in remote areas, there are a range of potential risks that must be managed. Although efforts to maintain a safe working environment began several decades ago, there has been a significant increase in expectations concerning workplace safety in the last 30 years.

Current status

Under modern mining regimes the responsibility for identifying and correcting health and safety hazards in the workplace is shared among all parties involved – employers, contractors, owners, supervisors and workers. Normally this requires everyone to co-operatively identify and control health and safety hazards, a requirement and responsibility generally enforced under regional and/or national legislation (i.e. labour acts, regulations and guidelines).

National laws are enforced by a workplace regulator that independently inspects, reviews, records and promotes workplace safety. The labour laws will also identify escalating enforcement protocols that the regulatory body will follow or use to ensure compliance with the act and regulations. This can include fines, corrective orders, work stoppages and criminal prosecution, depending on the seriousness of the infringement.

Regulatory and societal expectations

The message "keeping workers safe on the job" has resonated around the world. Providing assurance that workers will safely return home at the end of the shift and are capable of returning to work for their next shift is driven by the societal expectation that work will be conducted in a safe environment. Achieving this goal is underpinned by the implementation of strong regulatory controls and enforcement on safety in the workplace, combined with the efforts of often unionised work forces to advocate workplace safety. Significant support by the owners/operates in investing time, money, resources, training and materials to continually improve workplace safety, as well as to invest in their long-term work at the site, has been another crucial component of workplace safety. At the centre of these efforts are the workers and their family and friends, who play an important role in monitoring this partnership to ensure that all aspects work effectively.

Historical trends

Accident rates in the early phase of uranium mining reflected the risks that were an integral part of mining at that time. Often mines were small UG operations and occupational hygiene controls were limited. As well as the physical risks (such as rockfalls and handling/use of explosives), there were also health issues. Inhalation of silica bearing minerals in poorly ventilated areas increased the risk of contracting silicosis. Allowing workers to smoke in the contaminated air exacerbated the effect. High concentrations of diesel exhaust in confined spaces increased the risk of contracting respiratory disorders. These risks were far greater than radiological risks.

In addition, workers in historic mines were not always properly trained and provided with personal safety equipment (e.g. protective eye glasses, steel toed boots, hard hats, gloves and coveralls), usually did not have access to a second emergency escape route in UG mines, had poor communication systems, lacked medical aid, first responders and mine refuge stations for temporary safety (e.g. during a fire underground). Numerous fatalities at mine sites (not just uranium mines and mills) were a common feature of annual statistical summaries prior to the modern era of mining.

A marked improvement in health and safety performance has been demonstrated in all areas of modern mining. Modern mining generally has far better safety performance than other comparable industries (e.g. heavy industry, construction, transport and farming) and also in developed countries has better safety performance than industries generally considered much safer, such as retail and office work (Figure 2.1). Due to increased regulatory oversight, uranium mining generally has a better health and safety performance than other comparable mining industries. The net result is that the health and safety of the workforce is tightly controlled and the resulting performance is as good as or better than most other industries.

Development of leading practices

Since employers usually have the most control over the working conditions, they have the greatest degree of responsibility for the health and safety of their employees. The country legislation typically requires employers to provide, for example, a safe and healthy workplace, training in safe working practices and providing properly maintained safety equipment. The workplace supervisors appointed by the employer must be properly trained in order to oversee work practices and workplace conditions. The employer is also required to ensure that an effective occupational safety or health committee is formed with the workers or their representatives and that the committee works co-operatively to identify and resolve any safety or health concerns.

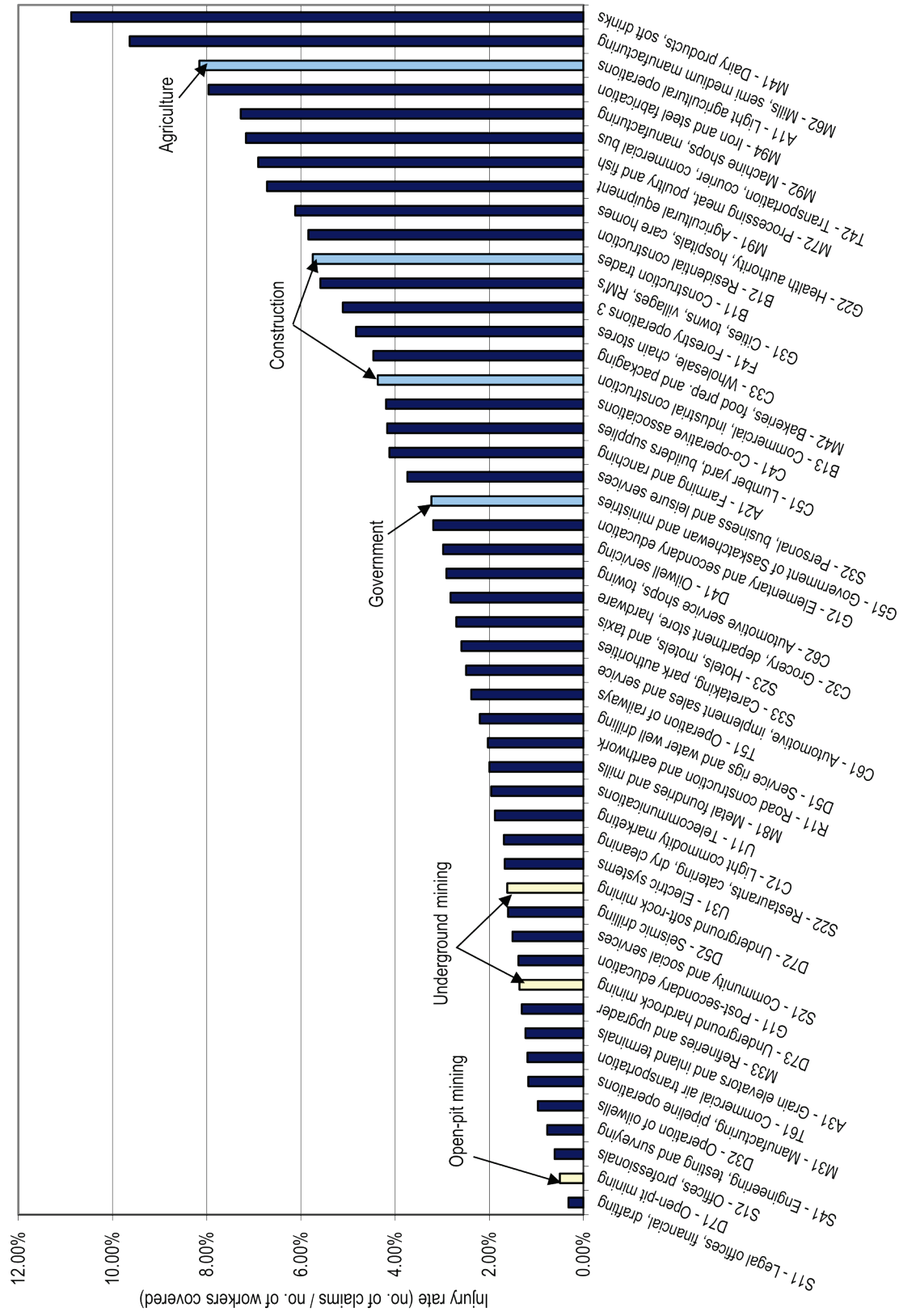


Figure 2.1. Saskatchewan injury rate by occupation (adapted from SWCB, 2010)

The supervisor's position is very important, as they are closest to the actual work being done and hence form a critical link between the employer and workers or contractors. They form the first layer of management to address and resolve worker concerns. The supervisor's duties include understanding and effectively communicating the company's safety programme, the use of personal safety equipment and the proper implementation of emergency procedures. The supervisor's primary role is to ensure that the workers understand their duties under the pertinent labour laws and know how to address findings or recommendations from the occupational committees.

The critical role of workers is to effectively implement their training on a daily basis to create a safe workplace. Their responsibilities include taking reasonable precautions to protect their own health and safety as well as that of their colleagues. All workers must correctly implement the training provided, follow safe work practices, make effective use of the safety equipment provided and co-operate with their site occupational committees. Workers are also responsible for reporting safety concerns internally and to regulatory authorities.

Case study: Historic uranium mining in the United States

Occupation health and safety is a vital aspect of uranium mining today. However, in the early phase of uranium mining, it did not receive the proper attention. This case study provides an overview of the situation in the United States, where the development of uranium mines in the Cold War took place rapidly when regulatory requirements and oversight had not yet been put in place. In addition, since many of the mines were small, privately owned UG operations located in remote regions, locals with no mining experience were employed. Without mining experience and adequate training in safe operating practices, accident rates were high. Experience from these early operations drove governments and industry to implement the necessary regulations, training and controls to significantly reduce accident rates in the mining industry.

Mines are hazardous environments and the possibility of fire, flood, explosion and collapse has the potential to affect a large number of workers. As outlined by Donoghue (2004), common causes of fatal injury include rock fall, fires, explosions, mobile equipment accidents, falls from height, entrapment and electrocution. Other hazards include noise due to drilling, blasting and other activities, heat and humidity at depth, whole body vibration from operating mobile equipment and diesel particulate exposure from powered mobile equipment. Fatal and severe traumatic injuries can have a profound impact on morale, at times leading to post-traumatic stress disorders. Psychosocial hazards (drug and alcohol abuses) can also be an issue, particularly in remote locations.

In the United States mining today is typically regulated by various entities with states playing a key role in oversight, although federal agencies are also involved. Development of conventional health and safety mine regulation in the United States, as elsewhere, was principally driven by numerous fatalities and injuries in coal mining, as summarised by the Department of Labor (DoL, n.d.a). The Federal Coal Mine Safety Act of 1952 provided for annual inspections in certain UG coal mines for the first time and gave the government limited enforcement authority, including the power to issue violation notices and imminent danger withdrawal orders. It also authorised the assessment of civil penalties against mine operators for noncompliance with withdrawal orders for refusing to give inspectors access to mine property (DoL, n.d.a). The first federal statute directly regulating non-coal mines did not appear until the Federal Metal and Nonmetallic Mine Safety Act of 1966 that provided for the promulgation of standards, many of which were advisory, and for inspections and investigations. However, enforcement authority was minimal (DoL, n.d.a). Moreover, at the time of early Cold War uranium mining, the

US Atomic Energy Commission (AEC) licensing authority did not come into effect until after the removal of the uranium from its natural source (Olson, 1959). It was in this regulatory void that the first uranium mining took place in the United States, principally in south-western states in the 1950s.

After initially depending on foreign sources, the AEC announced in 1948 that it would guarantee a price for and purchase all domestically mined uranium ore in the United States in order to alleviate the requirement for imports. This announcement initiated a uranium mining "boom" on the Colorado Plateau, overwhelming a more limited section of the mining industry centred first on radium and then vanadium, both of which occur with uranium in the same easy-to-mine, soft sandstone ore (Brugge and Goble, 2002).

As outlined by Ringholtz (1994), the AEC constructed roads into the back country, promised USD 10 000 bonuses for new lodes of high-grade ore, guaranteed minimum prices and paid up to USD 50 per ton for 0.3% ore, constructed mills, helped with haulage expenses and posted geologic data on promising areas tracked by federal geologists using airborne scintillometers and other radiation detection instruments. It also built several buying stations and a number of milling and reduction centres on the Colorado Plateau. In 1957 the Uranium Reduction Company opened the nation's first large privately owned uranium mill in Moab, Utah.

The programme was successful in increasing domestic production. As early as 1951, the AEC announced that the United States was second in uranium mining and processing in the non-Communist world and by 1955 was the leading producer of uranium ore in the world. By 1957, the emphasis was no longer on expanding production but maintaining and developing ore reserves for future needs. In a 1963 report to the President, it was noted that the United States was self-sufficient in uranium mining and milling (EEI, 2009). As military requirements were met, the AEC scaled back the buying programme in the early 1960s and stopped buying uranium from domestic mines in 1970 (Ringholtz, 1994), bringing this early phase of intense uranium mining activity to an end.

During the peak of the uranium mining boom, there were about 750 mines in operation in the Four Corners area of Arizona, New Mexico, Utah and Colorado (Brugge and Goble, 2002). Some of the mines were large OPs, but most were underground networks of shafts, caverns and tunnels shored up by timbers (ACHRE, 1995). Most were relatively small, situated in remote areas and operated by independent owners and lessees (Holaday, 1953). Although preliminary survey reports noted that potable water, adequate sewage disposal and occupational hygiene were lacking and medical facilities were practically non-existent, effective control of the operations was considered difficult to establish (Sinisgalli, 1949).

Early uranium miners often located mineralisation on surface exposures and followed the ore underground. As mining practices evolved and production requirements increased, mining techniques improved and productivity increased significantly. Between 1945 and 1962, over USD 2.5 billion was spent by the government, in addition to large amounts raised on the stock markets and UG mines were sunk to double and triple the depths of the older mines, some to over 800 m (Hahne, 1989).

Miners were paid minimum wage or less. The jobs included blasters, timber men (building the wooden supports in the mines), muckers (who dug the blasted rock), transporters and millers. Mining techniques ranged from pickaxe and wheelbarrow (Figure 2.2) to heavy equipment (Brugge and Goble, 2002). By 1954 some 1 000 uranium miners were working on the Colorado Plateau and employment peaked in 1960 at over 6 000, of which almost 5 000 worked in UG mines (FRC, 1967).

Although research on the health impacts of this early phase of mining has focused on radiological impacts on the workers, conventional health and safety accident rates were higher than today. Dhillon (2010) notes that the US metal (including uranium) and non-

metal mine fatality rate per 200 000 employee hours were 3 times higher in the 1950s than the period 2001-2005. Data collected by the Bureau of Mines, using voluntary responses to requests for information since there was no federal law requiring operators to submit information, show fatal and non-fatal injury frequencies of 0.136 and 9.724 per 200 000 hours in 1945 and 0.118 and 7.436 in 1954, respectively (Machisak et al., 1957). Although this early phase of uranium mining took place as the injury rate in metal mining throughout the country was in general improving, the fact that much of the mining was concentrated in remote areas and inexperienced miners were employed reversed this trend. Even though state inspectors were regulating activities to some extent at this time, the injury rate in uranium mines during the late 1950s was as high as experienced in other metal mines 15 to 20 years earlier (FRC, 1967).

Figure 2.2. Hand loading ore onto a wheelbarrow in a small mine on the Colorado Plateau in the mid-1950s (Dare et al., 1955)

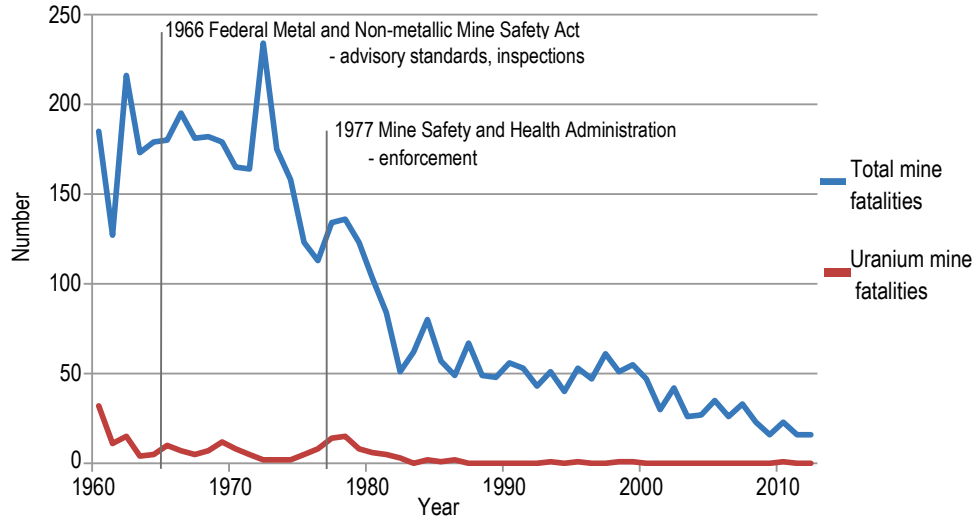


Reprinted courtesy of United States Department of Interior, Bureau of Mines.

In response to increasing health and safety concerns regarding uranium milling, the Energy Reorganization Act (ERA) was passed in 1974, leading to the creation of the Nuclear Regulatory Commission – NRC (EEI, 2009). At that time the NRC assumed regulatory control of uranium milling, enrichment operations and nuclear power generation. In 1977, the Mine Safety and Health Administration assumed enforcement responsibilities on its creation. Since then safer mining systems and methods have been introduced and an awareness of the importance of appropriate and effective accident prevention programmes by both miners and management personnel has grown (Dhillon, 2010), resulting in improved conventional health and safety in mining (Figure 2.3). In 2011, fatality and injury rates in the United States were the lowest recorded, with fatal injury rate of 0.0084 per 200 000 hours worked and the all-injury rate of 2.28 per 200 000 hours worked in the metal/non-metal mining sector (DoL, n.d.b). For uranium, the decline of UG mining and the development of ISL extraction in the 1990s also helped reduce accident rates.

The health and safety issues outlined above are not unique to the early phase of uranium mining in the United States. In the Czech Republic for example, Tomasek et al. (1994) noted increased risk of accidents, tuberculosis and non-infectious respiratory diseases in uranium mining cohorts that are considered a reflection of the dangerous and dusty conditions in confined working spaces. It was also noted that the rate of cirrhosis likely reflected the heavy drinking that was a part of the lifestyle of the miners, who were well paid compared to other Czech workers. Although most deaths were from accidents, homicide was a significant factor that was not considered in other studies of uranium miner cohorts.

Figure 2.3. Metal and non-metal mine fatalities in the United States, 1960-2012



Sources: US Department of Labor, Mine Safety and Health Administration century statistics (total), circulars and reports (uranium).

In (former East) Germany, the most frequent health issues for uranium mine workers after lung diseases and cancer were loss of hearing due to excessive noise, body disabilities caused by vibration, non-malignant skin diseases and spine damage. It can be concluded that these occupational diseases are typical conventional risks associated with this early phase of UG mining (Koppisch et al., 2000).

Improvements in mining practices and workplace hygiene that began during this early phase of uranium mining have resulted in a decreasing number of confirmed occupational fatalities, injuries and diseases. Legislative initiatives that established standards and compliance programmes further improved the situation. In more recent years, the introduction of safer and more productive mining machines and systems, ever-safer mining methods, a growing awareness of the importance of effective accident prevention programmes among both management and miners, combined with a more co-operative attitude toward safety issues by the mining industry, labour and government have improved accident awareness and reduced accident rates in all types of mining (DoL, n.d.b).

Case study: McArthur River underground mine, Canada

The McArthur River UG uranium mine, operated by Cameco Corporation, began production in 1999 after an environmental assessment process and rigorous review by federal and provincial regulatory authorities. The ore body, situated some 500 m below the surface, is large (about 150 000 tU) and high grade (some 10% U; Cameco, 2012), as much as 100 times higher grade than uranium deposits mined elsewhere. To protect workers from radiation exposure, mining is conducted using remotely controlled equipment, including underground crushing and grinding circuits. To protect workers from groundwater flooding, sections of the ore body and surrounding sandstone are frozen prior to mining. Safety is a core value from the CEO to the workplace and an array of programmes and procedures are employed to achieve high standards of worker health and safety. This case study outlines the main components of the conventional health and safety system that has achieved award winning success.

In the province of Saskatchewan, the only jurisdiction in Canada in which uranium is currently produced, mining is demonstrably one of the safest occupations (Figure 2.1). In terms of uranium mining, national recognition for safe working conditions has been achieved. In 2010, Cameco Corporation was awarded the John T. Ryan National Safety Trophy by the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) for having the best safety performance in the metal mine category for Canada (McArthur River had 2 lost-time injuries in 1 425 518 working hours in 2009). During development of the Cigar Lake uranium mine, Cameco was recognised with a Special Award Certificate by the CIM in 2009 (one lost-time injury for 729 344 working hours) and in 2005, the Rabbit Lake uranium mine and mill facility, also operated by Cameco, was awarded the John T. Ryan National Safety Trophy.

In Saskatchewan, workplace health and safety is governed by the Occupational Health and Safety Act 1993 (including amendments that came into force on 15 May 2013) and the Occupational Health and Safety Regulations 1996. The act and regulations apply to employers, supervisors, workers, self-employed persons, contractors, suppliers and owners. As summarised by the Saskatchewan Mining Association (SMA, 2012), safety training at mine sites in the province is continuous with new workers given an extensive safety training orientation (between 32 and 40 hours) supplemented with ongoing safety training. The Mine Safety Unit of the Occupational Health and Safety Branch of the Ministry of Labour Relations and Workplace Safety inspects all mines in the province on a regular basis. All mine working crews have regular safety briefings to ensure that safety is the first criteria considered before any task is undertaken. There are over 130 safety professionals employed by the mining companies in Saskatchewan and an additional 1 000 emergency responders trained at the mine sites.

In addition to strong provincial regulation, safety is a core value of the McArthur River mine operator from the CEO to the workplace floor, and working in a safe fashion is a required condition of employment (CIM, 2010). While there is a "safety programme" at McArthur River, it is the inclusion of safety in virtually all aspects of the mine that reinforces this value. Safety at McArthur River encompasses a number of programmes and processes that in combination provide a framework for a safe working environment and foster a culture of safety. By maintaining a focus on continual improvement and instilling safety as a condition of employment, McArthur River has achieved award winning results.

The unique geology of McArthur River uranium deposit presents several mining challenges. In addition to the risks posed by UG mining of high-grade ore, the presence of water-bearing sandstone enveloping the deposit poses a considerable flooding hazard. For these reasons Cameco uses a unique combination of a non-entry mining techniques and ground freezing.

All incidents at McArthur River are reported in the Cameco incident reporting system (CIRS) that is merged in a database with data from all other Cameco sites, facilitating cross-referencing and identification of trends and potential risks. CIRS information is used to train teams and to establish action plans to reduce risks. The company encourages employees to report every incident, no matter how small. This diligent reporting culture feeds other safety procedures on-site and builds a more concise picture of the operations. If incidents recur, safety supervisors can take safety stand-down action (i.e. a work stoppage) if they consider the recurrence serious.

Job hazard analysis is also used in instances where no existing procedures apply. All routine tasks have established procedures in place, but employees can find themselves at times facing unfamiliar situations. In these cases, the working group agrees on how the task will be done and writes up the procedure. If, when doing the task, it is decided to deviate from the written procedure, the group must come back together to agree on the altered approach. This system recognises risk and puts controls in place to mitigate risks. Job hazard analysis sessions can take place frequently, even on a daily basis.

Although the focus of a strong safety programme is preventing incidents and accidents, a mine rescue team and emergency response team are both in place and ready to assist when required (Figure 2.4). A great deal of training is allocated to these teams, which is not only an asset in case of emergency, but a clear signal of corporate support that underlines the company's commitment to safety standards to all employees.

Figure 2.4. Cameco mine safety briefing



Photo courtesy of Cameco Corporation, Canada.

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2.1.1. Worker radiation protection

To address the critical subject of radiation protection, it is important to first understand why regulatory measures are used to protect workers and the public from radiation, beginning with some basic concepts on radiation and the hazards it presents.

Radiation can be defined as energy travelling through space in the form of waves or particles. There are two forms of radiation – ionising and non-ionising. People use and are exposed to non-ionising radiation sources every day, but this form of radiation does not carry much energy and in general will not alter atoms or molecules. Examples of non-ionising radiation include cell phones, radios, cordless phones, microwave ovens, global positioning systems and even the earth's magnetic field.

On the other hand, radiation protection measures are necessary when ionising radiation is involved because this type of radiation has the ability and the energy to remove electrons from matter, thereby altering atoms or molecules. The affected cells

can repair some of the damage, but not quickly or efficiently enough to compensate at higher doses. For this reason, doses are carefully monitored and regulated by limiting the ionising radiation dose or exposure that workers and the public receive.

Ionising radiation can be naturally occurring or man-made (e.g. applications in nuclear medicine). Ionising radiation includes alpha particles, beta particles, gamma rays, X-rays and neutrons. These forms of radiation will be discussed in further detail in terms of uranium mining and the regulatory controls, radiation protection procedures and radiation monitoring that is employed in leading practice mining operations.

One significant advantage with radiation is that more is known about the health risks associated with it than with any other chemical or otherwise toxic agent. Radiation effects have been studied in depth in both the laboratory and among human populations since the late 1890s. With the establishment of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 1955, broad assessments of the sources of ionising radiation and its effects on human health and the environment have been undertaken. Those assessments provide the scientific foundation used in formulating international standards for the protection of the general public and workers against ionising radiation. A recent UNSCEAR (2010) report clearly consolidates and summarises the committee's detailed understanding of the low-dose radiation effects on health.

Current status

In uranium mines, even though radiation is naturally occurring it still requires extensive controls and monitoring to ensure that workers are protected. Workers in a uranium mining facility can be exposed to airborne radioactive contamination, like radon gas, radon progeny and long-lived radioactive dust. They may also be exposed to external radiation, like gamma rays from the ores, contaminated waste rock, or sludges and scales that accumulate in the mining or milling process. The prevailing radionuclide in the uranium ore is uranium-238, and the prime source of radiation in uranium mining and milling comes from the uranium-238 decay chain. Further details are provided in Table 2.1.

Radiation protection of workers is a core requirement for successful uranium mining. Under most circumstances, occupational exposures in the uranium industry are far below established dose limits (Clement, 2010). In addition, due to the extensive measures of modern radiation protection and controls at the uranium mine site the off-site public, even those nearby the operations, are protected.

Table. 2.1. Typical nuclide mixtures encountered in the uranium industry and their potential to contribute to external exposure

Sources	Radionuclide mix	Potential for gamma emitters per unit activity	Specific features
Ores	All present (γ:^{214}Pb, ^{214}Bi)	High	Radionuclides in equilibrium
U product	^{238}U, ^{234}U, ^{235}U	Low	Increases with time after separation
^{226}Ra scales	^{226}Ra, ^{222}Rn and RDP (γ:^{214}Pb)	Very high	Accumulations in vessels, pipes and rubber in mine and mill components
U scales	^{238}U, ^{234}U, ^{235}U and ^{234}Th, ^{234}Pa	Low	Accumulations in vessels, pipes and rubber in mine and mill components
Po/Pb scales	^{210}Po/^{210}Pb	Very low	Fine dusts, electrostatic precipitators

U = uranium; Pb = lead; Bi = bismuth; Th = thorium; Ra = radium; Po = polonium; Pa = protactinium; Rn = radon; RDP = radon decay product.

Regulatory and societal expectations

Established in 1928, the objective of the International Commission of Radiological Protection (ICRP) is to contribute to an appropriate level of protection against ionising radiation exposure without unduly limiting the benefits associated with the use of radiation. The optimisation principle of ALARA (as low as reasonably achievable, societal and economic factors taken into account) is the primary mechanism for reducing doses below dose limits and is a fundamental part of the modern radiation protection system. In the case of uranium mining, occupational doses are very dependent on the characteristics of the operation as well as the site-specific factors. For modern, leading practice uranium operations, full compliance with ICRP (1991) and IAEA (2011) recommended principles and dose limits is regarded as mandatory and leading practice facilities today operate at levels well below these limits.

Historical trends

Leading practice uranium mine and mills have very high radiation protection standards. Average occupational doses from uranium operations are lower than a number of other occupations generally thought of as not having radioactive hazards (e.g. the average uranium miner receives less radiation than an average international airline pilot). However, this has not always been the case and early practices in uranium mining did result in situations where workers and the public received doses which are unacceptable today.

During the military production boom in the mid-20th century, there was little knowledge of radiation health risks and virtually no radiation protection in uranium mining operations. This, combined with a strong push to maximise production at all costs, resulted in high exposure situations due to mining and processing practices that lacked proper dust control and adequate ventilation that led to high levels of radon build-up. Doses exceeding 50 mSv/yr (mSv – millisieverts) were common and at times exposures well over 100 mSv/yr occurred. These historical operations have subsequently been the focus of a range of epidemiological studies that have increased understanding of the risks and strengthened the radiation protection system. Dose limits have been adjusted accordingly and modern regulations limit exposures to 20 mSv/yr and 100 mSv over a 5-year period and occupational exposures in the industry today are typically well below these limits.

Development of leading practices

Significant improvements in radiation protection have been achieved through a combination of improved understanding of the behaviour and hazards posed by radioisotopes associated with uranium production activities, strengthened regulation and improved operational practices, as outlined below.

Occupational radiation protection

For uranium mining there are three major occupational exposure pathways: external radiation, inhalation of long-lived alpha activity (LLAA) and inhalation of radon decay products (RDPs). There are minor potential pathways from ingestion, injection or absorption of radionuclides, but normal occupational hygiene practices ensure that these are not significant. The dose from the relevant exposure pathways can be combined to provide the total dose for comparison with appropriate dose limits.

External gamma exposure

Uranium and its decay products have a range of gamma emitting radionuclides. Due to the comparatively higher energy of gamma rays they have greater penetrating ability and thus influence worker doses in proximity to the ore being mined and the vessels used in processing plants (mills). Exposure risks are low for the final uranium product because gamma exposure rates are small due to gamma rays being both low intensity and low energy. The most dominant contributor to gamma exposure in the final uranium oxide concentrate product is protactinium-234. When uranium oxide is freshly produced, the gamma signature is reduced as it takes time for protactinium concentrations to increase through radioactive decay (dominated by the 24-day half-life of thorium-234). Gamma exposure rates increase over a couple of months and can be a more important consideration during product transport.

External radiation is generally easy to measure and slow to change in a uranium operation. This means that controls can be well established that are strongly linked to the workers proximity to material with high uranium content. This is one of the dominant pathways in the UG working environment as workers can be surrounded by such material. Corrective measures to reduce doses include using mining methods that limit the time that personnel work in high-grade ore areas, the provision of cleaning areas to prevent the build-up of active material, active monitoring to keep personnel informed of higher dose areas and the use of shielding to reduce dose rates, such as the use of shotcrete (i.e. concrete or mortar injected onto a surface) for wall stability and gamma shielding, barren material for work platforms and providing shielded enclosures for long duration work areas. In processing, gamma ray exposure is more easily minimised due to the ability to control the interaction with process materials. Care may be required when dealing with scales that build-up in process areas as these scales could have high concentrations of radium-226 and hence a high gamma exposure rate.

Gamma exposure to personnel can be measured by either personal monitoring or area monitoring. The use of thermoluminescent dosimeters (TLDs) is a common low cost manner for accurately determining occupational gamma exposure on an individual basis that should be undertaken. However, a workgroup averaging approach can be used in less critical areas. Alternatively, an area monitoring approach can be undertaken where the time spent in a particular area can be used to estimate dose.

Inhalation of long-lived alpha activity (LLAA)

Within the uranium decay series there are a number of LLAA isotopes that can be an issue. When dust arising from uranium operations is inhaled, radioactivity may enter the lungs and be a source of internal exposure. Depending on a range of physical properties such as solubility and particle size, this material can stay in various areas of the lung, be removed from the body or be transferred to other areas in the body. These parameters, along with the radionuclide and the activity inhaled, all influence the resultant dose from an exposure.

Once separation of the uranium has begun during processing in a mill, disequilibrium occurs and the behaviour of individual radionuclides must be accounted for in order to determine dose. The most common separation is that the uranium goes into the product and the rest of the LLAA goes to tailings, but this is not always the case. To explain this further, and to achieve a better understanding of the detailed science and experiences gained in this industry, the following overview describes the pathways that specific radionuclides typically follow. Normally, the pathway for each isotope would be determined for each individual operation:

- Uranium-238 and uranium-234 are assumed to remain in equilibrium and are generally very well tracked as they are the production target. Uranium can be easily measured using chemical means and tracked accordingly.
- Thorium-230 behaviour is very dependent on pH and solubility. Initially it is either left insoluble within the tailings or at more extreme pH travels with the uranium in the pregnant liquor. It is generally rejected from the product stream during the final uranium extraction and added to the tailings. Free liquor (liquid) on tailings impoundments may have comparatively high concentrations of thorium-230, which may become an occupational or environmental issue if the liquor evaporates and the salts are dispersed.
- Radium-226 has a different shaped solubility curve than uranium so is generally sent for disposal with the tailings. However, if the tailings are neutralised or there are other near pH neutral stages, the radium may move from the liquor phase to form a scale coating on pipes and vessels. These scales can have high concentrations which if made airborne can lead to enhanced exposures. This can also occur in an area of the processing plant which is not normally associated with radioactivity.
- Lead-210 mimics the behaviour of natural lead, so its presence can be estimated relatively easily from conventional chemical measurements. Generally, it is quickly rejected and goes to the tailings stream in conventional processes. If however, there are any high temperature processes, there is potential for some airborne release due to volatilisation (i.e. turned into a vapour).
- Polonium-210 generally follows the lead, but is much more volatile. If there is any heating of the process streams, polonium may become a significant airborne hazard. As it is a pure alpha emitter, it is the hardest LLAA to measure and does not have a direct chemical mimic that can be used to estimate its concentration.

Control of exposure to LLAA is exactly the same as other controls on dust inhalation. Preventing dust generation is the best manner for controlling exposure and methods to do this can range from simple techniques such as regularly spraying water on surfaces, keeping material in the aqueous phase, cleaning up spills and covering dry material. For areas with higher potential exposures, such as during packing of the UOC, more sophisticated techniques can be used such as negative pressure rooms and respiratory protection equipment. Access to respiratory protection equipment is important.

Monitoring the inhalation of LLAA is generally similar to the occupational hygiene monitoring of dust. The most common method is the collection of either personal or airborne dust samples (using a pump and filter head) and determining the activity on the filter. What is the key in this case is that individual workers potentially exposed to LLAA are outfitted with individual personal samplers to measure their specific exposures. These measurements are further complemented by area or spot samples taken by the radiation protection staff during routine monitoring programmes. Monitoring and verification programmes ensure that internal exposures from LLAA are now minimised in the modern uranium mining industry.

Inhalation of radon decay products (RDPs)

Radon is naturally produced by the decay of uranium and is released into the air when uranium ore is mined and milled. As a result, controlling radon in uranium mines and mills requires engineering design and processes to remove radon from the workplace to limit worker exposures. Radon gas produced during mining and milling is continuously monitored, controlled and ventilated away from workers to avoid hazardous exposures. Presently, worker exposures to radon in the uranium mining and processing industry are as low as, or only slightly greater than, public exposures to natural radon.

In the uranium-238, uranium-235 and thorium-232 decay series, there are three naturally occurring radon isotopes that are decay products of radium. All natural isotopes of radon are alpha emitters. The half-lives of radon isotopes vary by orders of magnitude. Accordingly their potential impact varies.

Radon decay products (RDPs) are short-lived radionuclides that emit alpha, beta and gamma radiation but the majority of the dose arises from the alpha emitters. RDPs, formerly referred to as radon daughters or progeny, include isotopes of radon gas (referred to as radon-222, thoron-220 and actinon-219 respectively) produced from radium isotopes in the uranium-238, uranium-235 and thorium-232 decay chains. Thoron gas and decay products are only of importance in case of significant thorium mineralisation and actinon does not present an important occupational hazard.

Radon is relatively soluble in water and for this reason water transport can be a significant mechanism for radon dispersal. Radon can diffuse through porous media and moves through the air. Thus radon bearing waters seeping into an UG mine, or radon gas released from the groundwater and broken mine rock can be a significant contributor to a worker's exposure underground, if not controlled.

For mining operations where exposures are insignificant, the following approaches can be used to handle materials containing radionuclides:

- **Exclusion** for materials which have radionuclide content below a limit agreed upon with the regulator. This level is usually below the upper bound of normal soil radioactivity (approximately 1 Bq [Becquerel] per gram for each radionuclide in the U/Th decay chains, and 10 Bq per gram for potassium-40).
- **Exemption** in situations where exposures are within the scope of legislation but can be released from compliance because control is not warranted or no significant dose reduction is achievable by *reasonable* means (1 mSv/yr).
- **Intervention** in emergency or chronic exposure situations (e.g. "action levels" at gamma dose rate measurements of 0.5 mSv/h or airborne radon concentrations of 1 000 Bq/m^3).
- **Clearance** criteria for release of materials from within the regulated practices; these should be numerically the same as the exclusion criteria.

Because radon is an inert gas and only remains in the body for a short time, exposures are not generally a major concern unless radon is present in extremely high concentrations associated with very high-grade ores. However once radon is released from rock, it decays into a range of short-lived (half-lives of less than 30 minutes) decay products, which when inhaled can result in radiation exposure.

In UG operations, inhalation of RDP is one of the most important exposure pathways. This is due to the confined nature of the activity, which can allow both radon and RDP to build up rapidly if control mechanisms are not in place. For OP mining there is far less potential for RDP exposure, although OP mining at depth during periods of little air movement can increase the exposure potential. During processing, inhalation of RDP is generally a minor pathway. However, areas of poor ventilation (e.g. conveyor tunnels, vessel entries, degassing points) may lead to inadvertent exposures.

Radon and RDP in UG mines is of high importance because the levels of exposure can change rapidly (e.g. rising by several orders of magnitude in a single shift) if controls are not in place. As a result, inhalation of RDP is the exposure pathway that requires the highest level of active control and often is the most resource intensive in radiation protection measure in UG mines.

There are a number of approaches to controlling radon and RDP exposure. The most common involve either reducing the amount of radon entering a working area (e.g. shotcreting walls, reducing groundwater infiltration, closing off mined-out areas),

providing clean air to work areas (ventilation), reducing the residency time of the air (through ventilation, extractive systems), controlling occupancy time in high RDP areas (active RDP monitoring, action levels, time limitations) or by filtering out the RDP by using protective respiratory equipment. The success of these approaches is very dependent on the site-specific factors at individual operations.

Monitoring of RDP exposure is often complex and labour or equipment intensive. The most common manual method of sampling RDP is via grab samples, by taking a short duration (ten minutes or less) dust sample and then gross alpha counting after a suitable short delay by one of a number of different approaches. A person's exposure to RDP can then be calculated using the working time in the area along with the measured concentration. Alternatively, there are a number of automated instruments that can be used, but they can be expensive.

Total occupational doses

The ICRP recommends adding doses from all individual exposure pathways to arrive at the total dose. The total dose can be then compared to dose limits and used in the optimisation process. With modern uranium mining and processing techniques, compliance with dose limits is the norm and excess doses are rare. In fact, the current doses from uranium operations are generally well below regulatory limits and within the range of natural background variation. There is some variation dependent on the type of mining and processing and the quantity and grade of the ore being processed. Generally UG mining operations have the highest potential for exposure and ISL operations have the lowest due to the non-intrusive nature of the mining method and the relatively simple and contained processing method.

Worker radiation exposure at leading practice mining facilities

The success of efforts to control radiation exposures in the industry are depicted in Figure 2.5. In the early days of the mining industry, the understanding of the behaviour of radioactive particles and their inherent health risks was poor. With improved understanding, tightened regulatory controls and improved operational practices, worker exposures have been significantly reduced.

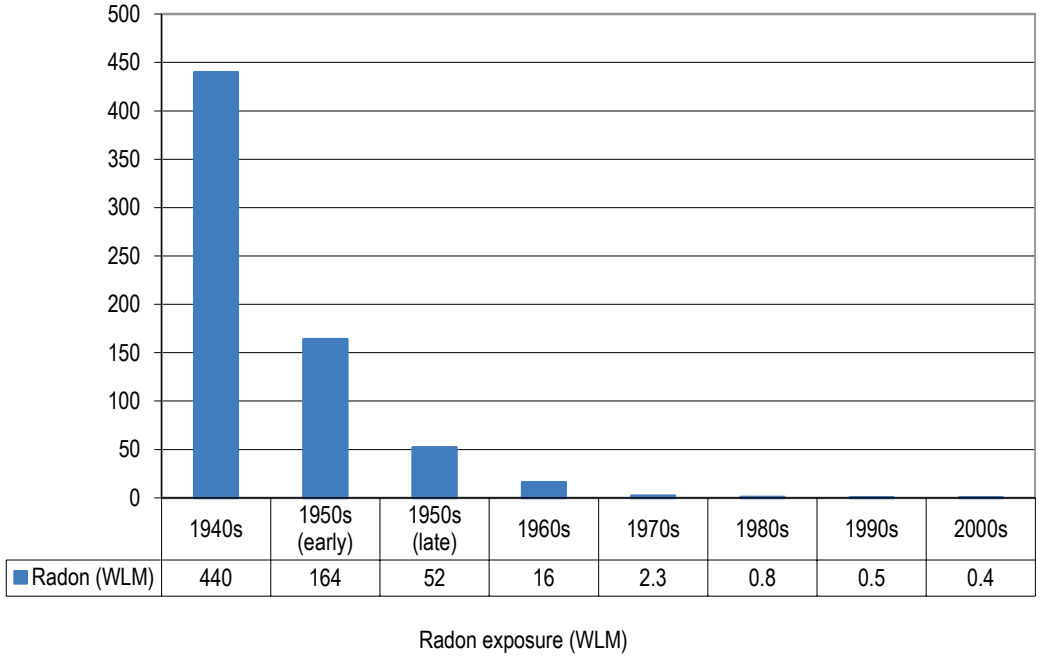
The dramatic improvements that have occurred in worker protection and radiation exposure are further illustrated by recent Canadian research. In the mid-1990s, a federal provincial environmental assessment of the development of several high-grade uranium ore deposits recommended that epidemiological studies be conducted on present and future uranium miners. A peer-reviewed feasibility study of conducting such an investigation was undertaken by SENES Consultants in co-operation with regulators and the mining industry. This study concludes that it would not be feasible to further investigate the risk of excess lung cancer in modern uranium miners because exposures today are so low that no health effects are anticipated (SENES, 2003). It also noted that it would be practically impossible to accurately correct for the effects of smoking and residential radon exposures, factors that would greatly impact the study results.

The improved working conditions, extensive monitoring and management of workplace exposures in modern uranium mines will ensure that exposures remain low. Exposure records are maintained and assessed to confirm the above findings remain valid.

Workers from 1970 to 2000 are included in the SENES study along with the total number of workers expected to be employed in uranium mines to 2030 (approximately 24 000). The predicted number of lung cancers was calculated using baseline lung cancer rates, radon exposures from 1970 to 2000, cigarette smoking rates, residential radon

exposures and other factors. For the period 1970 to 2030, it was estimated that about 140 miners would develop lung cancer, primarily due to cigarette smoking, and only 1 miner may expect to develop lung cancer from workplace radon exposure (Lane and Thompson, 2010). The improved working conditions, extensive monitoring and management of workplace exposures in modern uranium mines will ensure that exposures remain low. Exposure records are maintained and assessed to confirm the above findings remain valid.

Figure 2.5. Levels of RDP exposure in UG mines expressed in working level months (WLMs*) in Canada from 1940



* Cumulative radon exposure in mining is specified in WLMs. If 2 000 working hours are assumed per year, then 1 WLM = 5 mSv. A working level (WL) is equivalent to any combination of short-lived RDPs in 1 L of air that generates an emission of 1.3×10^5 MeV of potential alpha particle energy. A WLM equals the exposure to 1 WL for 170 hours (working hours per month). 1 Bq m^{-3} = 0.00445 mJ h m^{-3} and 1 mJ h m^{-3} = 1.4 mSv (ICRP, 1993).

Source: AREVA, 2011; CNSC, 2011.

Case study: Wismut mining health impacts, Germany

The uranium miners who worked in (former East) Germany, particularly prior to 1954, were exposed to high levels of radiation and other hazardous materials, resulting in serious workforce health impacts. This case study outlines aspects of working conditions that led to the high exposures and health impacts. From 1946 to 1990, (former East) Germany was the third-largest uranium producer in the world, employing on average 45 000 workers per year in UG mines or in mills. Between 1946 and 1990, more than 400 000 had worked in the operations and some 25 000 had contracted either silicosis or other lung diseases (mainly cancer) due principally to high exposures to radiation and other hazardous substances as a result of poor health and safety practices. Most of the miners were smokers and this behaviour undoubtedly contributed to the high incidence of lung disease.

Prompted by the first military use of uranium and the subsequent nuclear arms race, the Soviet armed forces occupying (former East) Germany began uranium exploration and mining activities on an unprecedented scale in the Ore Mountains in Saxony in 1945. The principle goal was to maximise production for the arms race. When it became apparent that the military was not the most suitable organisation to manage uranium production, the Soviet shareholders corporation, SAG Wismut was created in 1946 to oversee the activity.

SAG Wismut directed uranium mining and production until 1954, when the corporation was restructured into the Soviet-German shareholders corporation, SDAG Wismut. That same year uranium mining activities were extended into Thuringia. SDAG Wismut directed uranium production until German reunification in 1990. Both SAG and SDAG Wismut had a centralised organisational structure and were fully integrated into the Soviet military-industrial complex. Until the mid-1950s, about half of the workers were prisoners of war.

In order to meet targets established by the military, uranium production was sharply increased to 1954 by ignoring established mining standards (Enderle and Friedrick, 1999). For example, there was no forced ventilation in the UG mines and air exchange relied exclusively on natural processes. Dry drilling for mine development was used in hard quartz rock with high arsenic content, producing significant amounts of dust at the mining face. There were no provisions for sprinkling surfaces with water to control dust accumulation. Moreover, manual mucking (cleaning rock and other debris from excavations) and extended UG shifts further increased worker exposure levels.

Due to the lack of forced ventilation, dust removal from the constrained mining space was very slow, thus allowing the attachment of RDPs to dust particles. Because worker protection and radiation safety measures were totally lacking, miners were fully exposed to external gamma radiation and the inhalation of radon, short-lived RDPs, lead-210 (^{210}Pb), uranium dust and dust containing arsenic and quartz.

The first radon measurements and radiation protection measures in the mines were implemented in 1955; the most significant being the introduction of forced ventilation and wet drilling. However, individual radiation protection measures and adherence to international radiation protection standards were not introduced until 1970.

These poor working conditions took a heavy toll on worker health. Even prior to the reunification of Germany in 1990 more than 5 000 miners were confirmed to have contracted occupational diseases and had been granted compensation. The most common diseases were silicosis, lung cancer, extra-pulmonary cancer, bone and liver cancer.

After reunification, SDAG Wismut was restructured by the German federal government into a national remediation company. This company (Wismut GmbH) responded to requests from public stakeholders interested in viewing and working with the "historical" records of SDAG Wismut. The historical record of greatest interest was the radiation monitoring and worker health records. These records formed the basis of a meticulous epidemiological study of working life doses of the former miners. The extensive company archives (medical files for approximately 30 000 employees including 400 000 slides and approximately 66 000 tissue specimens from autopsies, including 200 whole lungs) were declassified to facilitate this investigation and international comparisons.

One finding of the retroactive assessment of exposures was that miners working in the Czechoslovakian uranium industry on the opposite (east) side of the Ore Mountains between 1946 and 1954 had considerably lower exposure levels than those on the western (German) side of the mountains. This is somewhat surprising since the uranium ore and the mining methods were similar and uranium production targets in both countries were maximised by the Soviet government. The most likely explanation is that

the production in Czechoslovakia was managed nationally, while Wismut was managed by Soviet (initially military) directors and supervisors who demanded longer shifts from UG miners in order to meet production requirements.

The retrospective assessment of Wismut miner exposures was initiated by the German Federal Institute for Occupational Safety and Health and the German Federal Agency for Radiation Protection. It included the development of models, comprehensive measurements under reconstructed working conditions and medical studies. The purpose was to create a job-related basis for addressing compensation claims and to enable preventive epidemiological research.

The scientific-medical part of the investigations focused on causes and consequences of exposure to radiation and the inhalation of dust, quartz and arsenic. To conclusively relate occupational exposure to a diagnosed cancer type requires additional information to complement the histological study of tissue, such as data regarding the individual's job-related exposure history, cumulative exposure, age, time of first and last exposure, time of cancer development and personal health (in particular smoking habits). In the exposure models developed by Jacobi et al. (1992, 1995, 1997), three time periods are distinguished: 1946-1954 – when radiation protection measures were totally lacking; 1955-1970 – when radiation protection measures and other actions were gradually implemented; and 1970-1990 – when individual radiation exposure measurements were routinely carried out and international guidance on dose limits was followed by implementing a radiometric control system.

To quantify the amount of dust inhaled by the miners, the original equipment was used under the working conditions of the specific period (Figure 2.6). The reconstructions of working conditions for the early period (1946-1955) showed that the average density of the respirable dust was as high as 15-20 mg/m^3 and respirable quartz density was above 2 mg/m^3. The radon and RDP level was as high as 350 working level months (WLMs) per year (an average lifetime dose is 200 WLM). For reconstructed working conditions in the period 1960 to 1980, the fine dust density in the air decreased to 1-2 mg/m^3 and the radon and RDPs exposure level dropped to 4 WLM/year (see Figure 2.5 for an explanation of WLM). Based on these reconstructions, job-exposures per shift were derived.

Although the typical arsenic content of the loaded ore was in order of 5 g/kg, the medical files showed that arsenic-related diseases were not frequent, indicating that the arsenic content of the inhaled dust was of lesser significance to worker health. Nonetheless, the possibility of synergetic effects of arsenic and radiation could not be dismissed.

Figure 2.6. Parking lot and mine shafts at Schlema uranium mine with waste rock piles in background, 1965



Photo courtesy of German Federal Ministry of Economics and Technology.

Investigation of the lung tissue of miners deceased by the year 2000 revealed 16 692 cases of silicosis and 7 963 cases of lung diseases caused by radiation exposure (mostly lung cancer). Approximately 200 cases per year are added to this total (Koppisch et al., 2004) as surviving mine workers age.

The next most frequent health issues were loss of hearing due to excessive noise (5 034 cases), body disabilities caused by vibration (4 838 cases), non-malignant skin diseases (630 cases) and spine damage (534 cases). It can be concluded that the dust and radiation-related diseases were caused by high exposures during the "unregulated" mining practices in the early period (1946-1960), whereas the other occupational diseases are typical conventional risks associated with UG mining. The gradual improvement of the mining practices and workplace hygiene that began in 1955 and continued into the 1970s is reflected in the decreasing number of confirmed occupational diseases. However, the number of cases of silicosis and lung cancer is expected to diminish slowly.

Investigations by Taeger et al. (2006) showed that in 30.6% of lung disease cases, silicosis accompanied lung cancer. Prior to 1955, miners and mill workers were commonly exposed to radon and RDPs at levels that annually amounted to the life exposure dose level of 200 WLM (equivalent to 1 000 mSv). The records of 13 000 Wismut employees provide an average occupational exposure level of 725 WLM; in the case of approximately 800 workers the exposure levels were as high as 1 800 WLM (i.e. 9 000 mSv), orders of magnitude higher than current limits of 20 mSv/yr and 100 mSv/5 yrs.

The cumulative exposure to radon and RDPs in cases of lung cancer were on average 552 WLM. A statistically significant increase in the risk of lung cancer was identified for cumulative exposures above 800 WLM. After accounting for various co-factors, the relative cancer risk was estimated to be 0.24 per 100 WLM. The largest relative risk of lung cancer was found for miners who worked prior to 1960.

Taeger *at al*. (2006) suggested that the double exposure of miners to RDPs and quartz dust, in spite of different biological impact mechanisms, may accelerate cancer development. Because it is known that RDPs are inhaled with the dust particles that they are attached to, the assumption of a synergetic impact is considered likely. Equally, it is known that the residence time of radon (gas) in the lung between inhalation and exhalation is too short to contribute substantially to the overall exposure. It is the inhaled RDPs that become deposited in the lung which provide the deleterious exposure.

A disadvantage of the Wismut miner's medical files is that the records do not provide reliable data on smoking habits. Thus, an important cancer risk factor cannot be taken into consideration. It is, however, known from the "Wismut hearsay" that non-smoking miners were the exception, and it seems reasonable to assume that all Wismut miners were smokers.

Case study: Olympic Dam radiation protection, Australia

Radiation protection at the Olympic Dam mining facility is a matter of priority for the continued operation of the facility. As in other modern operations, powerful ventilation systems are used to avoid the build-up of radon in the UG workings and worker doses are closely monitored through the use of TLD badges combined with area measurements in the facility and detailed accounting of time employees spend in each work location. Adoption of a code of continuous improvement means that the radiation protection system is constantly reviewed for potential improvements. Through these efforts, radiation exposures to workers in the mine and metallurgical plant have been reduced despite the fact that they were already well below required regulatory limits.

Uranium is produced at the Olympic Dam UG mine in South Australia as a co-product of the primary product copper. In over 20 years of production, the operator has maintained a strong focus on protecting employees, contractors and members of the public from radiation using design and management practices. Radiation protection programmes are designed according to the ALARA principle to maintain doses levels that are as low as reasonably achievable, social and economic factors taken into account (BHP, 2009).

Officers of the Environmental Protection Authority (EPA) of South Australia regularly travel to the site for radiation review meetings and compliance inspections. Longer visits may be undertaken, such as when an officer stayed the site for a week to observe operational radiation monitoring and radiation safety practices at the mine and processing plant (EPA, 2012).

As required the current mine operator, BHP Billiton (Olympic Dam Corporation) Pty Ltd, submitted an Annual Radiation Report and LM1 Annual Licence Report for the operation (EPA, 2012). These reports, reviewed by the EPA Radiation Protection Committee, included an assessment of the adequacy and effectiveness of radiation protection measures. The 2010-2011 dose summary is typical and indicated that the mean dose for all designated workers in the mine and processing plant was 2.9 mSv and 2.0 mSv, respectively, compared with the 20 mSv average annual limit for radiation workers. The maximum individual dose received during that fiscal year was 7.1 mSv (35% of the 20 mSv limit).

At the Olympic Dam operation a focus is placed on continuously reducing employee doses (BHP, 2010). Some of the measures used to reduce exposures include approval of a new radiation management plan, use of continuous RDP monitoring equipment, continuing use of electronic gamma dosimeter monitoring programme (and a trial of new instrumentation), extensions to the existing ventilation system and focused radiation monitoring for the higher exposed work groups.

The main exposure pathways for mine workers are the inhalation of RDPs, irradiation by gamma radiation and inhalation of radioactive dust. Assessments of exposure from dust, fumes and RDP are based on employee time sheet/card information and measurements made in the approved monitoring programme. Database records include employee name, employee number, occupation, date, work location and hours in location. Locations within the mine are grouped into areas of “like air”, known as airways. The senior ventilation engineer or their nominee familiar with the underground environment maintains the locations within the airways.

The RDP concentration is determined for each airway on a weekly basis using measurements from the monitoring programme that covers the most active work areas. For work airways not sampled in that week, an average is calculated from all readings for that particular airway over the quarter.

Employee exposure to radioactive dust is calculated using quarterly occupation-based averages. The averages are obtained from monitoring performed under the approved monitoring programme. An occupation-based dust concentration level is then allocated to each occupation.

The occupation-based dust concentration information and location-based RDP concentration information is then combined with the employee time card information to derive individual exposure data. Exposure details are combined to give quarterly personal exposures.

The entire procedure is processed using a software programme known as the Integrated Radiation Information System. The system is designed such that the Radiation Safety Officer is required to perform checks in each step of the process. This is in addition to a built-in auditing system within the programme.

Respiratory protection in the form of airstream helmet respirators are available for all employees and are worn during tasks identified as requiring their use. Airstream helmets are also mandatory for identified specific tasks or in certain conditions. Routine and non-routine use of airstream helmets is monitored and logged.

Exposure to gamma radiation is assessed using TLD badges from the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) personal monitoring service. TLD badges are worn for a period of three months; non-badge wearers are allocated an occupation-based average exposure.

The mine ventilation department focuses on ensuring that exposure to RDPs is minimised. This has been achieved by continued control over interactions in the mine through improvements in the eight-day and three-month schedules, installation of new fans for additional air volumes, extending the air intakes and implementing load sharing connections to provide extra air capacity to improve conditions in areas of concern.

The main exposure pathways for metallurgical plant workers are the inhalation of radioactive dust and fumes as well as irradiation by gamma radiation. Assessment of exposure from dust and fumes follows the same methods as outlined above for mine workers. Dust exposure in the metallurgical plant may involve exposure to different types of dust of specific particle size and radionuclide composition, which will produce different dust dose conversion factors.

Although the exposure to RDP within the metallurgical plant is much less than other pathways, it is assessed in the same way as for mine workers. The same time information used for calculation of dust exposure is used for calculating RDP exposure. All surface locations/occupations are grouped into one surface airway. A weekly average is calculated from all surface RDP measurements and is assigned to this airway. Location-based RDP concentration information is then combined with the employee time card information to derive individual weekly exposure data.

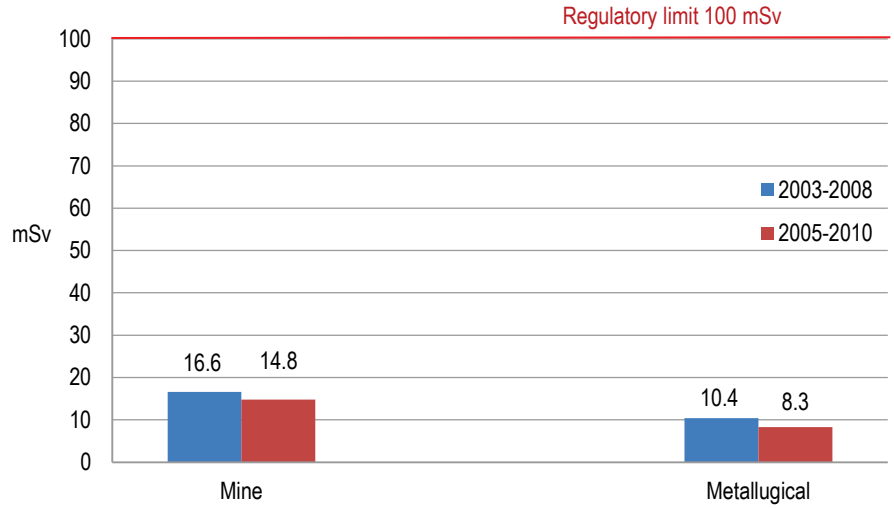
As outlined by the ICRP (1991) and codified in regulatory requirements, the total dose of any individual radiation worker should not exceed 100 mSv in any 5-year period. Accordingly, five-year total doses have been determined for all full-time currently designated mine workers who were employed at the facility for the previous five years. The calculation of cumulative 5-year effective dose includes employees who have worked for more than 18 quarters.

There were a total of 471 designated miners who worked continuously during the period 1 July 2005 to 30 June 2010. The maximum dose for a mine worker is 31.3 mSv for the 5-year period ending 30 June 2010, as compared with 33.4 mSv for the 2003/2004 to 2008/2009 5-year dose period (Figure 2.7). The arithmetic mean for the group was 14.8 mSv, a decrease from 16.6 mSv for the 5-year dose period 2003/2004 to 2008/2009.

A five-year total dose has also been determined for all metallurgical plant employees at Olympic Dam. There were a total of 371 currently designated metallurgical plant employees who worked continuously during the period 1 July 2005 to 30 June 2010. The maximum dose for the 5-year period was 32.4 mSv, compared to the value of 41.7 mSv calculated in 2008/2009. The arithmetic mean for the 5-year dose period for the metallurgical plant has decreased from 10.4 mSv to 8.3 mSv.

All values are well below the 5-year regulatory limit of 100 mSv. With the operator's commitment to continuously seeking improvements in the radiation protection system and regular inspections by regulators, maintaining exposures well below regulatory requirements is ensured. Despite being well below regulatory limits, the company works to reduce exposures continually.

Figure 2.7. Mean five-year dose period determinations for mine and metallurgical plant workers at Olympic Dam compared to regulatory dose limit for radiation workers (100 mSv over five years)



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2.2. Public health and safety

Current status

On average, about 60% of the radiation doses that humans receive come from nature, or are deemed "naturally occurring". The sun and naturally occurring radioactive elements like uranium and radium in the earth and the radioactive gas radon are all sources of radiation that humankind is exposed to. Other sources include the ingestion of small amounts in the food and drinks consumed and man-made radiation through medical treatments, mainly from procedures like X-rays and cancer treatments. These can account for up to almost 40% of annual average exposures.

By comparison, nuclear activities (including uranium mines and nuclear power plants) release small quantities of radiation to the environment, amounting to about 0.6% of annual human exposures. Scientific studies show that such releases do not pose a health or environmental risk and radiation releases are carefully controlled and authorised by the countries' regulatory authorities (CNSC, 2013). It is within this context that the element of public safety for nuclear activities must be understood. Considerable effort at all levels of government is made to protect and monitor the environment and the public who are off-site from any nuclear facility.

These regulatory obligations are prescribed in leading practice laws and regulations, with independent authorities overseeing the nuclear facilities and continuous monitoring

of any emissions or releases from the site in both near-field and far-field locations. In turn, monitoring data are evaluated and assessed or modelled in detail to ensure that the public and the environment off-site are not at risk. These results are further peer reviewed and released for public scrutiny and public information.

Regulatory and societal expectations

Despite forming a very small part of human exposures, the process of mining uranium releases radon into the atmosphere and can lead to the release of uranium and other heavy metals if not properly managed. Radon is a colourless, tasteless gas and exposures in excess of regulated limits can increase the incidence of cancer. Uranium is toxic and ingestion above regulatory limits can cause health impacts, such as kidney failure. As a result, some members of the public express concerns about the potential for being exposed to above regulated limits of radon, uranium and other potential hazards, particularly when residing in close proximity to an active uranium mine. Society today expects that no person's health should be impacted by industrial activities like mining.

As a result, every country regulating nuclear facilities and nuclear safety have regulations to ensure public land, air and water (both surface and groundwater) are protected now and in the future. Since the off-site environment includes the public, environmental protection will also protect the public.

Historical trends

The radiation dose to members of the public from uranium operations is driven by local site-specific factors. Doses during operations, even historically, have generally been relatively low (typically a small fraction of the natural background dose). The most significant public doses are typically associated with the post-closure phase of the operation when restrictions on site access can be either lifted or ignored, allowing direct exposure pathways to dominate in cases where sites have not been properly decommissioned or remediated.

For situations where the public does not have direct access to the site, the inhalation of RDP and direct or indirect ingestion of material have historically dominated. Control of radon release from some historical operations has been poor and, due to the proximity to population centres, has on occasion resulted in significant exposures. Erosion of tailings and waste rock facilities has led to contaminants (either solid or in ground/surface water) entering food production areas and hence becoming a potential exposure pathway.

Examples of actions that have given rise to directly enhanced public exposure include inappropriate use of mined material, "recycling" of discarded equipment and inappropriate land use. Tailings material, due to its sand-like properties and ease of handling, can appear to be a very useful surface base building product and when used in this fashion can cause enhanced exposures. Similarly, low-grade ore and waste rock used for dwelling construction will increase public exposures. During closure, discarded equipment and surplus materials have often been disposed of on-site in areas such as tailings storage facilities or evaporation ponds. These materials are subject to scavenging and unauthorised access can result in unacceptable doses due to the need to dig through radioactive material to obtain the desired items, some of which may be radioactively contaminated. Land and resource use, such as grazing on mined areas, use of groundwater and habitation directly on rehabilitated areas, have all also occasionally led to enhanced public exposure.

Development of leading practices

The separation of the public from the immediate direct sources of exposure is generally sufficient to ensure doses remain low, even though in the early history of uranium mining the apparent risks from radiation were little known. Practices to reduce dust emissions, such as restricting emanating areas to a minimum size and number and keeping tailings moist can reduce total emissions. During rehabilitation, radon emissions can be substantially reduced by installing a cover on radon emitting facilities.

Proper remediation and closure of facilities, including public education, posting of warning signs in addition to placing proper covers on tailings and problematic waste rock greatly reduces exposure risks. In cases where remediation has not been properly completed, the continued exclusion of the public from higher risk areas through zoning and land use controls or warning signs reduces the potential for increased public exposures.

Public radiation exposure pathways

During the operational phase, the principal exposure pathway is radon emanation and subsequent airborne dispersal resulting in the inhalation of RDPs. Dust generation and subsequent inhalation of LLAA, can also be significant in certain situations as can the impact on groundwater with local use. Post closure, more localised impacts tend to dominate, including direct gamma exposure, direct or indirect ingestion and inhalation of RDPs and LLAA.

Emanation of radon and subsequent inhalation of RDPs

Radon gas is released during mining operations, processing and from waste management areas such as tailings and waste rock. The ability to reduce the radon emission from an operation is relatively limited, but practices such as restricting emanating areas to a minimum size and number and keeping tailings moist can reduce total emissions. During operations, keeping the public some distance from the facilities generally ensures that natural atmospheric dispersion of the radon is sufficient to keep public exposures well below regulatory dose limits. Studies in Canada show that within a very short distance from uranium mining and milling facilities (usually around the site's licensed boundaries), radon concentrations are close to background levels as determined by reference sites far from the facility (CNSC, 2011).

During rehabilitation, radon emissions can be substantially reduced by installing a cover on radon emitting facilities. Methods for reducing radon emanation during rehabilitation generally revolve around the use of sealing covers (e.g. clay layers) to prevent the radon escaping before the gas decays due to its relatively short half-life (3.8 days).

Care must also be taken that uranium (or specifically radium-226) bearing material is not used for the construction of dwellings or local structures. If used in this way, there is significant potential for higher than recommended doses due to the build-up of radon in the dwelling structures. Similarly, construction of dwellings on mining wastes with significant radionuclide content can result in significant RDP exposure unless there is adequate sealing of the radon in the waste repository.

One of the most significant issues in calculating the operational exposure to RDPs is the natural background levels of radiation. In some areas, natural concentrations exceed 1 mSv/y and therefore it is important that these are not included with operational contributions. There are a number of ways to separate operational from background contributions, including the use of pre-mining background levels, remote background

sites and wind direction correlation. The dispersal of radon can be measured (either using continuous measurements or inexpensive track-etch detectors) or RDPs can be directly monitored.

Dust generation and subsequent inhalation of LLAA

The inhalation of LLAA by the public, as a result of dust generation from uranium activities, is generally a relatively minor pathway. However, for large OP mine facilities in dry areas it can become significant. Dispersal of dust can also result in secondary exposure pathways such as movement of material onto cropping areas.

Controls on dust generation include minimising the dust generating areas, using barren cover, keeping dusting areas damp and implementing controls on dust discharging process areas. During operations, one area of particular importance is associated with the final uranium product due to its high specific activity. Active controls (e.g. baghouse, scrubbers) are often used to reduce this potential discharge.

Monitoring of dust exposure includes use of active air sampling, passive dust collectors or more novel approaches such as sticky paper collectors or moss collectors. Similar to RDP it is important to remove the natural contribution to this exposure pathway. This may be done by the use of pre-mining background levels, remote background sites or airborne dispersal modelling.

Direct gamma exposure

During the operational phase of a mine, members of the public are generally excluded from close proximity to the facility. Because gamma exposure decreases rapidly with distance, this is generally a negligible pathway during the operational phase. The importance of direct gamma exposure arises when the site is closed and handover has occurred. This generally involves the removal or reduced effectiveness of institutional controls to prevent public access. The residual facilities left after closure can be attractive for the development of dwellings (i.e. unpopulated areas cleared of vegetation, topographic highs with local "rock" sources for building, etc.).

Control of gamma exposure involves discouraging prolonged close proximity of the public and the use of barren material to provide shielding against gamma exposure. Long-term institutional controls can be put in place to prevent construction on rehabilitated areas (e.g. zoning controls, land use controls or warning signs), however, these are prone to failure. Using waste rock as a shield is a very effective method of preventing gamma exposure. However, the ability to use this is driven by a combination of economics and availability of the material. For OP operations this is generally feasible, but for UG operations the presence of shielding material may be scarce and the use of any cover will need to be optimised.

Ingestion of LLAA

There are many potential ways by which LLAA may enter the ingestion pathway. These include direct ingestion of material (e.g. soil by children or from campfire cooking), crops grown on soil containing operational material, use of groundwater or surface water (e.g. for drinking, crops, livestock, consumption of livestock or wild animals that have been on the operational area). Although historically this has been significant in a small number of cases, it remains one of the primary issues of public concern.

Controls during operational phases revolve around restricting the generation and dispersal of material. This includes dust controls, restricting discharges to the aquatic environment and controls on emissions to groundwater (and potentially the local use of

groundwater). During rehabilitation, one of the primary considerations is the isolation of material from the environment. This includes measures to reduce the potential long-term impact on groundwater, erosion controls to prevent surface water impacts and cover sequences to prevent biological penetration of tailings structures.

Monitoring for this pathway generally involves environmental sampling and radionuclide determination. However, care is required because of natural variability. In a number of cases the operational component may be far smaller than the natural background levels. In such cases, the operational component can be determined and taken into account.

Total public doses

For modern mining operations, public doses are generally restricted to a small fraction of the public dose limit and are typically much less than pre-existing local natural background radiation. At these low dose levels there will be no significant impact on local communities either during operation or post closure.

During operations, doses are actively monitored and assessed. Generally the most challenging aspect of this assessment is separating the operation-related component from the often larger natural background component. Radon dispersal and subsequent inhalation of RDPs dominates and other pathways are generally not significant. For example, data from 6 current ISL facilities in the United States show doses to potential off-site human receptors range between 0.004 mSv/yr and 0.32 mSv/yr, both well below the annual radiation dose limit for the public of 1 mSv/yr (NRC, 2009). The CNSC (2013) notes that numerous studies have shown that uranium mining and milling activities do not increase radon levels in the environment away from the mine sites and there are no significant health impacts on the public living near uranium mines and mills.

During rehabilitation and as part of handover, consideration of public dose is critical. The use of passive structures to ensure isolation of the material from the general environment is a core component. Measures may also be required to prevent human intrusion into rehabilitated structures and care should be taken to ensure no high-value items are left in the facility (or even rumours that such items might be left behind). However, there are a number of very positive examples of successful remediation giving rise to long-term containment with little potential for significant public exposures.

Case study: Schlema radon issues arising from past practices, Germany

Uranium mining and processing in (former East) Germany during the period following World War II was characterised by complete disregard for the environment and "reckless encroachments on population centres" (BMWi, 2011). The Schlema site in south-west Saxony is an example of the results of these historic practices conducted in the midst of local population centres. Proper treatment, sorting and storage of waste rock would have considerably reduced the environmental impacts of mining and the public health hazards resulting from these out-dated practices.

The Schlema area was mined from 1946 through 1990, producing about 80 000 tU. During the course of mining operations, an extended waste pile landscape was created at and around the site of the historic Oberschlema spa (one of Germany's most renowned radium spas, first developed in 1918). During mining, the spa and town were obliterated as waste rock was dumped in the town's centre and at other locations nearby (Figure 2.8).

By the late 1950s, the Oberschlema deposit was exhausted. Abandoned mine shafts were for the most part backfilled with waste rock and to some extent plugged. Surface subsidence as well as local near-surface mine voids were also backfilled, but no

systematic mine rehabilitation was undertaken. As mining-induced surface cave-ins and subsidence continued to occur, larger portions of the town area had to be fenced off and the community subsequently degenerated into wasteland.

Figure 2.8. Waste rock piles, Schlema, 1960

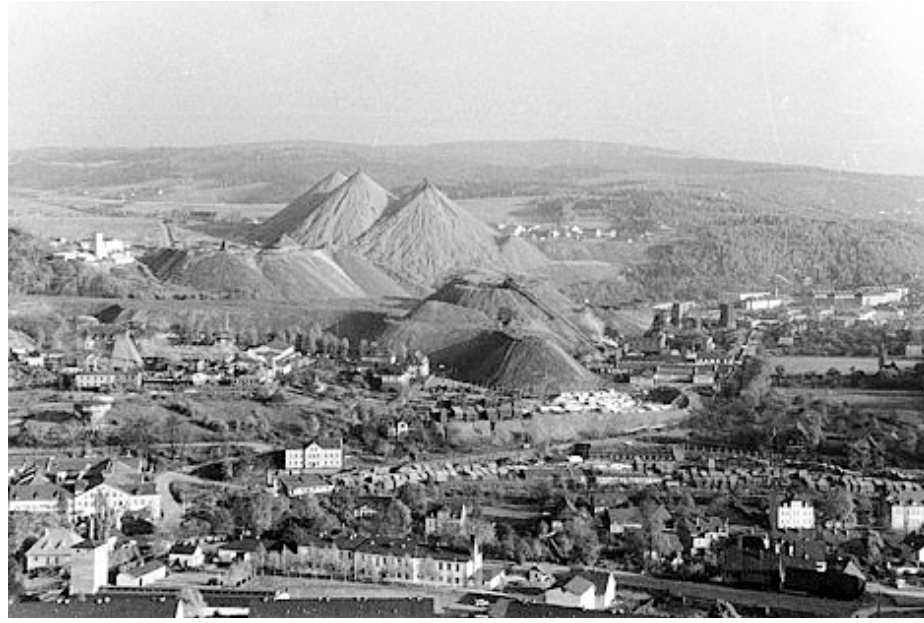


Photo courtesy of Wismut GmbH, Germany.

In addition to the physical devastation, the waste rock piles in Schelma contained the highest radon concentrations of any closed uranium production facilities in (former East) Germany. The 20 large waste rock piles and stockpiles of low-grade ore have mean specific ^{226}Ra activities of 0.4 to 2.0 Bq/g, high enough to require remediation in order to comply with radiation protection legislation. During operations however, this rock material was simply piled against hill slopes around the settlements located in a valley. By the time uranium mining had depleted the local deposits, more than 47 million m^3 of waste rock had been accumulated, covering a surface area of 342 ha (Schmidt et al., 2008).

At sites with considerable waste rock concentrations like Schlema, the prevailing radiological hazards are due to radon exhalation. Under unfavourable settings and meteorological conditions outdoor radon concentrations may accumulate and reach 2 000 Bq/m³. Where possible, a large volume of waste rock can be used to backfill an OP mine (e.g. Ronneburg), otherwise waste rock piles must be reshaped to a stable form and covered *in situ*. In these cases, the cover design must reduce the radon exhalation rate to an acceptably low level.

The remediation concept at Schlema-Alberoda consisted of stabilising and protection by reshaping and covering the waste rock piles. To optimise cover construction, investigation of soil-air transport processes and cover layer designs showed that radon exhalation from the piles is dominated by air convection. The convection process is driven by air temperature differences within the pile and in the outside air that create pressure differences that drive radon exhalation. Consequently, the radon exhalation rate and radon concentration in the free air show daily and seasonal fluctuations.

An optimised cover construction was conceived to be built of inert material of 1 m thickness (Figure 2.9). The installation of this type of cover brought about a reduction in

the radon exhalation rate and, in turn, a significant reduction in radon concentration at the site (by a factor greater than ten).

Figure 2.9. The cover design used for waste rock piles with increased radon exhalation rate

Thickness		Structure/functionality	Soil parameters of relevance
0.2 m		Re-cultivation layer (to enable plant growing)	
0.8 m		Radon barrier (thickness > radon diffusion length; to depress air convection)	- Gas permeability - Proctor density - Water saturation point - Wilking point
		Waste rock	

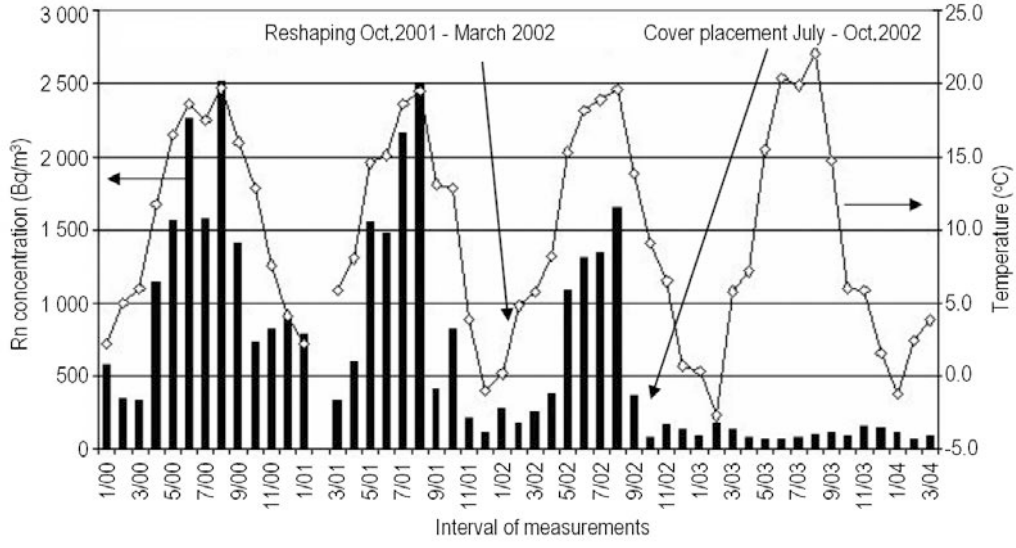
Reprinted courtesy of A. Jakubick and P. Schmidt/Wismut, Germany.

The effect of remediation of a pile adjacent to a residential building is shown in Figure 2.10. The correlation between radon exhalation (solid bars) and temperature (lines above bars) is clear prior to cover placement in October 2002. After that date, the correlation disappears and radon exhalation is considerably reduced.

In the immediate vicinity of Schlema and in Alberoda, the waste rock pile landscape has been completely re-cultivated through remediation processes. At other waste rock piles substantial remedial work has been completed. Post-remedial maintenance and long-term tasks are being performed in order to ensure long-term success. In the vicinity of waste rock piles, remedial progress has been clearly demonstrated by sharply reduced airborne radon concentrations, sufficiently reduced at many sites to achieve compliance with radiation protection standards. At some locations work is continuing to further improve the situation.

Favourable urban development following comprehensive rehabilitation of the Soviet-era mining legacies is exemplified in Bad Schlema, where tourists have returned and the title of "spa town" has been regained (BMWi, 2011).

Figure 2.10. Radon concentration levels in the air close to the toe of a waste rock pile before and after remediation



Reprinted courtesy of A. Jakubick and P. Schmidt/Wismut, Germany.

Case study: Long-term public radiation doses from radon in uranium mill tailings

Radon emissions from uranium mill tailings have been and continue to be raised as an issue of concern to those living in the vicinity of currently operating or closed uranium mining and milling facilities. While the issue remains controversial, research conducted some years ago demonstrates that the public health risks posed by uranium tailings facilities are low. Although aspects of this study are subject to revision with additional information and, given a 10 000-year time horizon, conclusions are inherently uncertain, the results show that modern practices (i.e. tailing facilities that are saturated and water covered) significantly minimise public health risks associated with uranium mining facilities to the point that the risks can be considered insignificant.

In the late 1990s, the Uranium Institute (precursor to the World Nuclear Association – WNA) commissioned a study to estimate the long-term public health impact of radon emissions from global uranium mine tailings sites and this case study outlines the work and conclusions of this study by Chambers et al. (2001). One goal of the study was to update an earlier assessment (UNSCEAR, 1993) by using more up-to-date and site-specific data. Since long-term (10 000 years) population doses are evaluated, estimated radon release rates exclusively from tailings after decommissioning were considered (releases during operation prior to decommissioning are of relatively short duration – generally less than 50 years – and were not considered). The 10 000-year length of the long-term evaluation was chosen by UNSCEAR "for the sake of illustration".

The approach taken by Chambers et al. (2001) in selecting the sites for the study was to focus on mines in operation between 1995 and 1997. The major uranium production facilities in operation at the time were examined in order to provide a snapshot of modern and likely future conditions of tailings management sites. Most of the facilities chosen remain in operation today (Chambers et al., 2001). Site-specific information on radon release rates, tailings volumes, ore grades and production rates, likely decommissioning plans and population densities were collected from the operators of the facilities. The data gathered was representative of 67% of worldwide uranium production in 1997.

ISL facilities were not included in the study because they do not produce surface tailings and little in the way of radon emissions after closure. At the time, ISL facilities contributed only about 13% of worldwide uranium production. Hence, the information used in the study was representative of 80% of worldwide conditions at the major uranium production facilities under current and foreseeable future tailings management practices.

Access to air dispersion information for North America from previously completed projects, as well as census population data for Canada, allowed more site-specific analyses were carried out on the Canadian sites (three of the eight sites in the study). Access to these data facilitated estimates of population doses using both actual and uniform population distributions as well as air dispersion factors measured for a northern latitude and a mid-latitude site. By means of this comparative analysis, the variability in the population doses and long-range dispersion factors for two such different locations were investigated which, in turn, assisted in quantifying the potential uncertainties associated with the use of the same dispersion estimates for all tailing sites.

Combined with an updated estimate of tailings area required for global nuclear generation capacities, radon release rates based on measurements from 8 active tailings sites, representative population estimates and other factors, models with comprehensive meteorological data and the radon decay rate showed that radon concentrations drop off rapidly by a factor of 1 000 at a distance of 100 km from the active tailings site (Chambers et al., 2001). The mean concentration is significantly lower at a distance of 2 000 km and

continues to drop with increasing distances due to both ongoing dilution and radioactive decay. The incremental radon levels at all distances were shown to be much lower than typical natural outdoor radon concentrations.

Since concentrations decrease rapidly with distance, the actual distribution of population within the area can significantly impact the population exposure. The long-term (10 000 years) population dose estimates for the uranium tailings sites examined in this study yielded normalised estimates ranging from 0 to 5.9 person-Sv/GW/yr, with an overall 1997 production weighted average of 0.96 person-Sv/GW/yr (these estimates assume that 210 tU is required to produce 1 GW/yr of electrical energy from a generic nuclear power plant). The exposure estimates derived by Chambers et al. (2001) using site-specific data are about a factor of 150 lower than the UNSCEAR (1993) estimates that relied on generic radon emission and population data.

People living around the eight sites examined in this study will also be exposed to background radon, irrespective of the operation of uranium production facilities. Background concentrations in areas with uranium deposits are generally higher than typical background levels.

Uncertainties include long-term changes in population density around uranium production facilities and limitations imposed by using data directly from 80% of the facilities in operation at the time. Nonetheless, the total long-term (10 000 years) population dose to radon emissions from the uranium tailings sites examined is about 4 650 person-Sv. This converts to about 280 cancers over 10 000 years, or less than 3 cancers over a typical lifetime, assuming a conservative linear-no threshold (LNT) dose response model. This compares to the more than 60 million background cancers expected in the lifetime of the approximately 210 million people living within 2 000 km of the sites examined (assuming a 30% background cancer incidence rate). The rapid increase in the use of ISL production since the time that this study was conducted (in 2012 over 40% of global uranium production) would reduce overall emissions from tailings considered in this study, as would the reduced uranium requirements in recently constructed nuclear power plants.

The population doses estimated in the study implicitly assume the validity of the LNT dose response model; that is, the risks of exposure to radiation are assumed to be directly proportional to the dose received down to a dose of zero. There is much discussion about the appropriateness of the LNT model for estimating impacts from doses that are extremely small fractions of natural background radiation. The presence of a dose threshold, even a practical threshold in which competing causes of death defer the risk from radiation beyond the expected lifespan for detrimental effects, would greatly reduce any assumed impacts associated with the population doses estimated in this study.

The study concludes that the radon concentrations associated with tailings emissions are extremely small on both a relative (compared to typical background levels) and absolute (in terms of dose and risk) level. The individual risk of cancer associated with the predicted radon concentrations is below a level that can be considered completely insignificant and trivial (Chambers et al., 2001). Moreover, if decommissioned tailings are water-covered the radon source term is eliminated.

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2.3. Water quality

Mining encounters water in or near mine workings, uses water in extraction processes and mining activities can be undertaken in the proximity of water sources important to both human and non-human biota. Uranium mining and milling may also be undertaken in dry regions, where water is not readily available for make-up or process water and must be pumped into the site from a considerable distance. Alternatively, mining can be undertaken in environments characterised by large amounts of seasonal rainfall, where management of excess water periodically may require significant planning and effort.

All waters discharged from a mining site (clean, treated or wastewaters) are directed into adjacent lakes, rivers or streams, into evaporation ponds, or are injected back into the groundwater regime. Water management and the control of water, either reporting to the site or discharged or diverted from the site, are major activities at a leading practice uranium mine site that can be costly and challenging. Ensuring that overall water quality is protected is of paramount importance to the success of the operation.

Current status

Water management at a mine site involves a wide range of actions, including the control of water inflows to mine workings (surface and groundwater), liquid effluent discharge, fresh water diversions near the mine, mill and waste management areas and surface water runoff from precipitation events. By intercepting or diverting clean water, collecting contaminated water and treating effluents (chemically and/or physically), the receiving environment can be protected from mine site water releases. Ultimately, mine operators must control water inflows for the safety of miners, protect the receiving environment and minimise the amount of water which requires costly pumping and treatment. In the end, any excess water must be returned to the biosphere or injected underground.

Leading practice uranium mining and milling facilities are subject to a comprehensive EIA prior to beginning operation. During the subsequent licensing process, follow-up environmental and performance monitoring programmes are developed and implemented to monitor the potential effects of the operation with respect to the modelled predictions. These programmes also identify specific remedial actions in the event the receiving environment begins to exhibit changes in quality exceeding pre-

operational design targets. Compiling a comprehensive baseline environmental data set prior to beginning operations is critical to determining if changes have occurred in the receiving environment after operations have begun.

Regulatory and societal expectations

It is the expectation of society that uranium mines and mills operate in a manner that protects critical elements of the environment like water resources. To meet this expectation, protecting water quality is one of the key issues at a mining facility. An in-depth EIA before the final planning and design stages are undertaken. The EIA defines the environmental baseline conditions and determines, among other issues, if there is potential for the project to pose a significant adverse environmental effect or impact on water resources (both groundwater and surface water). Both EIAs and facility design make use of advanced models in geochemical, geotechnical and hydrogeological contaminant transfers and some form of environmental impact modelling.

Today, water quality standards are designed to protect ecological health, either in the immediate receiving environment at the end of the process pipe from the facility or further downstream in the mixing zone. High performance standards by the operator, effective regulatory oversight, comprehensive monitoring programmes and public engagement are all key factors in dealing with water quality issues.

Historical trends

Historically, early mine practices did not employ adequate control and treatment techniques, resulting in the contamination of local watersheds, nearby low-lying areas and, in some cases, impacts further downstream. Over time, especially since the 1970s, standards for water releases were strengthened. Initially these improving standards were designed to protect subsequent human use of water resources, but more recently have been further developed to protect non-human biota (fish, flora and fauna) and groundwater resources.

As a result of out-dated practices, environmental impacts from historic uranium mining and processing sites in several countries include elevated concentrations of trace metals (e.g. arsenic, copper and zinc), radium-226 and uranium in water. Draw down of groundwater resources and groundwater quality impacts have also been observed. Untreated site releases from historical operations have exposed populations of aquatic and terrestrial non-human biota to elevated levels of radionuclides and other hazardous substances, leading to measureable food chain impacts.

Poorly planned and operated uranium mining facilities can produce more severe environmental impacts when natural events such as seasonal runoff, intense rainfalls, earthquakes or droughts lead to the off-site release of contaminants. Historically, some facilities were not adequately designed and constructed to withstand such events. For example, the failure of an above-ground tailings facility dam could lead to significant human health and environmental impacts due to the sudden release of significant amounts of ponded water, solid tailings and sludges into rivers and lakes, onto roads or even into neighbouring communities.

Some of the most significant health impact legacies of these early operations were brought about by the widespread distribution of site contaminants. Whether transported by bordering streams that are subsequently used for irrigation and watering livestock, or by wind into neighbouring communities from waste piles or dried, uncovered tailings, the health impacts can be chronic until remediation is undertaken. All of the above historical practices and consequences were key drivers in improving the design and operation of uranium mine facilities so that all potential impacts are minimised to acceptable limits.

Development of leading practices

OP, UG and ISL mining techniques almost always encounter groundwater. For the protection of workers and the efficacy of mining, water inflows must be controlled through interception and diversion techniques. When it can be intercepted before coming into contact with mineralised zones, groundwater may be simply collected and either used or released back to the environment, with little or no treatment. On the other hand, for groundwater that enters mine workings, and/or comes into contact with mineralised zones, treatment is typically required before it can be released. Depending on water quality, treatment can be as simple as reducing suspended solids, or if necessary, can require multi-phased treatment and filtering techniques. In warm and dry climates, evaporation can also be an effective means of reducing releases.

In some cases, *in situ* freezing techniques are used to immobilise groundwater to reduce mine inflow in addition to improving ground stability. Diversion techniques intercept clean water before it encounters sources of potential contamination so that the water can be rerouted or used with little or no treatment.

The quantity and quality of water to be treated at a mine facility is affected by a number of factors, such as:

- local hydrology and hydrogeology;
- the mining method and the characteristics of the ore and waste rock produced;
- the processing method in the mill and tailings that are produced;
- the siting and operation of all the waste management areas in terms of inflow, seepages, runoff, recycle and diversions.

A key objective of wastewater management and effluent treatment is to minimise the volume of water requiring treatment. The primary action is the interception and diversion of groundwater and surface water that would otherwise come into contact with mine workings or waste management facilities. When planned for and implemented correctly, the operator can effectively prevent contamination of significant quantities of water and reduce the need for long-term treatment over the life of the facility.

This can be achieved by:

- intercepting groundwater around mines and waste management areas with dewatering wells up-gradient of the facility or mine;
- diverting clean surface water around or away from mining operations;
- lining mine shafts with concrete or grout or constructing a freeze wall to minimise groundwater inflows;
- collecting and using mine water or contaminated site waters for use as mill make-up or industrial feed waters to minimise the use of freshwater for industrial purposes;
- reusing treated wastewater for mill process water or producing reagents.

In terms of effluent treatment, the operator must collect and treat all contaminated water to meet acceptable standards prior to release. To ensure that there are minimal effects from effluent discharge on the specific receiving environment, the operator and the regulator must fully understand the characteristics of the receiving environment (i.e. back-engineer from the environment to the treatment facility). Both parties must ensure that the treatment plant design will protect the near-field and far-field environment from both harmful concentrations of contaminants of concern, as well as total environmental loadings over the long term.

Modern uranium mine and mill facilities make use of dual-stage or multistage treatment systems, depending on the contaminants of concern. Dual-stage systems can include chemical precipitation and neutralisation. Multistage systems allow the operator to target more specific contaminants using more complex treatment processes. For example, the treatment of molybdenum and arsenic requires an initial lower pH stage, then the addition of ferric sulphate followed by an effective solid and liquid separation step to remove the precipitated contaminants prior to the increased pH treatment stages.

Where multiple contaminants of concern are present and high-quality effluent is required, the use of membrane technologies, such as the reverse osmosis process, can be applied. This process is non-specific for different contaminants but is energy intensive due to the fine membranes used. It also requires extensive chemical and standard filtration pretreatment processes to remove suspended and some dissolved solids, resulting in a smaller quantity of more saline and possibly contaminated wastes that must be dealt with appropriately. Although expensive, it is effective.

Environmental protection policies, programmes and procedures are important components in designing an effective environmental monitoring programme, especially to protect both surface and groundwater. A good environmental monitoring programme prevents unreasonable risk to the environment by confirming that the control measures on releases or emissions are effective and through the early identification of required remedial actions. Overall, the demonstration of the effectiveness of controls, through effluent and environmental monitoring activities, is a major part of an environmental protection programme.

Groundwater

The current status of protection, monitoring and groundwater sampling programmes for uranium mining and milling facilities vary around the world. For uranium mining and milling the IAEA has produced the following guidance:

- IAEA (1993), *Uranium Extraction Technology*, Technical Reports Series No. 359, Vienna.
- IAEA (2001) *Manual of Acid In Situ Leach Uranium Mining Technology*, IAEA-TECDOC-1239, Vienna.
- IAEA (2002), *Management of Radioactive Waste from the Mining and Milling of Ores*, Safety Guide No. WS-G-1.2, Vienna.
- IAEA (2005), *Guidebook on Environmental Impact Assessment for In Situ Leach Mining Projects*, IAEA-TECDOC-1428, Vienna.
- IAEA (2009), *Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development*, IAEA Nuclear Energy Series NF-T-1.1, Vienna.
- IAEA (2010), *Best Practice in Environmental Management of Uranium Mining*, IAEA Nuclear Energy Series NF-T-1.2, Vienna.

Countries that successfully manage groundwater impacts have developed regulatory criteria to achieve the following goals:

- **Prevention:** Leading practices are designed to prevent or reduce environmental contamination, including proper siting, development of engineered tailings management facility (TMF) and the use of radon barriers and liners. In addition, some countries either dry tailings or treat tailings to reduce the potential for groundwater contamination once tailings are placed in a final disposal area. Management approaches vary, but the primary objective is the long-term isolation of tailings from the public and the environment to control the release of contaminants and to reduce radon exposure. Once milling is complete, long-term care and surveillance is required to ensure that potential future exposures and

environmental contamination due to long-lived radionuclides and hazards from radon and seepage are recognised and appropriately dealt with.

- **Site characterisation:** Adequate characterisation of the subsurface is required to determine critical aspects of the underlying geological structures, groundwater flow direction and velocity and depth to groundwater zones. A thorough understanding of these fundamental characteristics is required in order to develop a comprehensive groundwater monitoring plan.
- **Monitoring:** A comprehensive monitoring programme prevents unreasonable risk by confirming that release control measures are effective. An adequate groundwater monitoring programme will detect potential leaks from operations, including impoundments. Adequate soil sampling must be included. The goal is to provide an early warning that mitigation measures are required to prevent or minimise impacts from site releases.
- **Remedial action:** A corrective action plan must be designed and implemented should a leak or spill be detected. The purpose of the corrective action is to prevent further migration of contaminants and to restore areas affected to levels that protect human and non-human biota and the environment according to standards developed in each country.

Case study: Taboshar legacy site, Tajikistan

The Taboshar legacy uranium facility is an example of how a lack of planning and regulatory control combined with outdated mining and milling practices led to significant environmental impacts, some of which remain to be resolved today. Uranium mining began in the 1940s and was followed by establishment of a processing plant that was rapidly expanded, eventually processing a variety of ores from several satellite countries using a variety of methods, leaving behind tailings and other wastes of varying chemistry. Neither a remediation plan nor a monitoring programme was established. The continued use of the site and materials from it, including contaminated water, combined with the spread of contaminants from uncontained waste dumps, has increased the area of contamination and the risk of human health impacts.

During the 1970s and 1980s, more than 30% of uranium production in the Soviet Union (USSR) came from the central Asian republics (Voystechivich et al., 2011). The extensive production at a time of limited environmental and health regulation left behind a significant legacy of mine and processing wastes. The mining and milling technologies applied throughout this area originated from the same engineering unit of the Ministry for Medium Scale Machine Industry. As a result, uranium production legacies in Central Asia, Eastern Europe, the Russian Federation and Ukraine exhibit similar characteristics and the remediation of these legacy facilities commonly faces similar challenges. The practices used included placing waste piles on the most convenient location with little or no regard for potential environmental and health impacts or subsequent remediation after the production facilities were closed. Maximising production was the primary objective of these operations.

With the collapse of the USSR, the institutions that had been responsible for common economic policies in this sector were dissolved and the newly independent central Asian countries became responsible for the management of natural resources. Thus the uranium industry in the newly independent states had to face the realities of the world uranium market if production was to continue. At the time, the uranium market was stagnant and the spot market price was about USD 20-25/kgU (USD 7.50-9.50/lbU_3O_8).

In addition to low prices, growth in environmental awareness resulted in the adoption of increasingly more stringent uranium mining and processing regulations. The combined effect of these circumstances was that most conventional uranium mines in Central Asia became uneconomic and had to be shut down by 1995. The only production facilities that remained in operation were the low-cost ISL operations. The closure and decommissioning of the conventional uranium mines took place at a time when technical and regulatory experience in these areas was poorly developed and adequate funding for remediation was not available.

The first uranium mines in the USSR and the oldest uranium production legacy sites are situated in northern Tajikistan. In the Taboshar area, small scale uranium and radium mining began in 1942 and uranium production was expanded considerably as early as 1945. A new, large scale processing plant was established and by the end of 1945 had processed approximately 10 000 tonnes of uranium ore to produce 7 tU. By 1946, 35 000 tonnes of uranium ore had been processed and by the end of 1947, the facility was expanded to process 176 000 tonnes of ore, producing about 25 tU. In 1948, production was doubled.

In the early stages of production, ore came only from the Taboshar area, but in order to increase output, increasing quantities of ore were transported to the site for processing from as many as 18 more distant mines, including Ungursoy (Uzbekistan), Maylu-Suu and Tuyuk-Suu (Kyrgyzstan) and others further afield, such as Jáchymov (Czech Republic), the Wismut mines (former East Germany) and mines in Bulgaria and Mongolia.

The steep increase in production stabilised only after 1950, but by then more than 600 000 tonnes of ore per year had been processed. The widely varying range of tailings at the legacy sites in this district is due to the fact that these first uranium processing facilities in the USSR were receiving ores with varying mineralogy and grade. Moreover, processing technology development occurred as uranium production continued.

The Taboshar mining and processing facilities are perhaps the most significant legacy of these early operations in terms of health impacts on local populations. In addition to the health impacts caused by the contaminated site itself, additional impacts are likely due to the spread of contaminants via streams draining the mountainous site to agricultural plains near the Uzbekistan border where the water is used to irrigate crops. The health impacts of this site are chronic in nature due to continuous spread of contaminants from the waste piles into the city, settlements and the valleys of the waterways draining the site (Jakubick et al., 2008).

The Taboshar legacy site is complex and extends over 400 ha. The legacy wastes comprise a large OP, two abandoned UG mine access points, two waste rock piles, the abandoned structure and bunkers of the low-grade ore processing facility, a pile of ground, low-grade ore next to the processing plant that had been prepared for leaching (known as the Yellow Hill of Taboshar; Figure 2.11) and several tailings piles connected to the developmental stages of the hydrometallurgical process plants used to recover uranium.

From a radiation protection point of view, the Taboshar site is a public health issue because contaminated water is used by locals and the proximity of the legacy wastes to Taboshar (12 000 inhabitants) and Old Taboshar. Because both modern and historical monitoring data are lacking, an accurate assessment of the impact of these legacies on the local population cannot be determined until an investigation of all pathways for contaminant migration is completed. Nonetheless, it is clear that the important radiation protection issues are associated with the:

- use of the water discharging from the UG mine access point and the OP mine;
- location of the Taboshar school at the entrance of the legacy site, just above the location of the former ore processing plant;

- use of the site by the local population for grazing domestic animals, collecting materials for construction (e.g. tailings sand) and the utilisation of the remaining scrap metal;
- use of the contaminated parts of the valley and banks of the local drainage streams by locals for outings and picnicking;
- presence of small farms, orchards and kitchen gardens in the valleys.

Figure 2.11. Taboshar "Yellow Hill" of ground ore prepared for heap leaching



Photo courtesy of A. Jakubic, Uranium Mining Remediation Exchange Group (UMREG).

The largest radiological impact on the local population is most likely the result of the direct use of contaminated water due to a lack of alternate water resources. However, other sources of radiation include the flooded OP mine above the road connecting Taboshar city and Old Taboshar, two waste rock piles located just above the Old Taboshar settlement, the low-grade ore pile in the vicinity of the processing plant and the tailings piles.

Following the closure of mining activities, limited remedial measures were undertaken at the tailings sites, following procedures specifying that the tailings surface be covered with a one-metre-thick neutral soil cover. During various IAEA visits to the site it was found that the tailings cover thickness does not exceed 0.5 m and often is not more than 20 to 30 cm.

The border between the tailings site and the city of Taboshar is unstable and portions of the tailings piles are actively being eroded by fast flowing streams. Considerable amounts of the tailings slid downslope in mudslides during the heavy rains of 1998 to 2000, spreading the tailings over a distance of more than 3 km in the valley. During the same period, spills from the other tailings piles took place. Small scale releases also occur regularly during the spring season, commonly activated by burrowing animals, mechanical excavations, tailings seepage and other disturbances of the tailings surface.

The greatest challenge to remediating the environmental and health issues at Taboshar has been funding. Based on the results of the European Commission's (EC) mission to Tajikistan, Kyrgyzstan and Uzbekistan in 2012, a number of projects have been identified and recommended for EC funding. At the end of 2012, financial agreements

were signed between the EC and the governments of these countries to conduct EIAs and feasibility studies prior to the remediation of a number of regional legacy sites, including Taboshar.

In addition, preliminary projects have been prepared to mitigate acute and chronic problems requiring immediate/short-term remedial action. Rapid remedial intervention actions are foreseen for, among other things, the construction of a water treatment plant for mine discharge at Taboshar. The appropriate financial support of the EC for environmental assessment, feasibility studies and remedial intervention projects has been approved and the projects are expected to begin in 2013.

Case study: Key Lake water management, Canada

The Key Lake operation is an example of a site that has evolved over several decades of operation as on-site ore sources were mined-out and new regional ore sources were mined and transported to the mill for processing. Water management has been and remains a key issue for the operator and regulators since mine development began. The collection and treatment of water are major activities at the site. Baseline environmental data collected prior to site development, along with an extensive monitoring programme throughout the life of the facility and consideration of the predicted impacts during the environmental assessment phase, have been used to objectively determine the operation's potential impact on the local environment and to successfully adjust water treatment programmes as concerns or improvements are identified. Environmental monitoring shows that aquatic impacts do not extend beyond the boundary of the facility and are within effect levels predicted.

The Key Lake operation is a key source of uranium supply in the global nuclear industry. By the end of October 2009, the Key Lake mill had, in total, produced more than 144 000 tU, with annual production accounting for about 16% of world production in recent years. After 26 years of production, the operator (Cameco Corporation) sought regulatory approval to extend the life of the operation. This case study focuses on issues and practices associated with water management. Unless otherwise indicated, the information presented below is based on the detailed project proposal submitted as part of the process to extend operations (Cameco, 2010).

Key Lake is located in the boreal forest region of northern Saskatchewan (Figure 2.12). Exploration beginning in 1970 led to the discovery of two orebodies in 1975 and 1976. Baseline environmental data collection commenced in late 1976, as did dewatering and surface water preparations. An environmental impact statement (EIS) was submitted to Saskatchewan Environment in 1979.

In December 1979, the Key Lake Board of Inquiry was established to conduct a public inquiry into the probable environmental, health, safety, social and economic impacts of the proposed project. The results of the environmental baseline work were summarised in the environmental assessment report presented to the Board of Inquiry. In addition to baseline conditions, predicted effects were identified for air quality, surface water, aquatic ecology, hydrology, geology, soils, vegetation, archaeology, socio-economic factors and radiological concerns. The inquiry was conducted in 1980 and the final report issued in 1981, following which the province approved the proposed development.

In 1983, the Key Lake mill began processing ore from two on-site deposits and continued until 1997. Tailings from the milling of these two deposits were placed in an above ground TMF. Cameco then applied for and received approval to develop a new TMF in a mined-out OP, where tailings were to be subaqueously deposited following engineering works. This proposal was also the subject of an environmental assessment. In 2000, following another environmental assessment and regulatory approvals, the Key Lake mill began processing ore slurry from the high-grade McArthur River mine (average

grade of about 15% U), which is transported to the site by purpose-designed trucks and blended down to about 4% U with special waste rock before entering the mill process circuit.

Figure 2.12. Key Lake uranium mill



Photo courtesy of Cameco Corporation, Canada.

The environment surrounding the site is well understood as a result of extensive studies conducted since baseline environmental data were originally collected. Numerous environmental monitoring programmes and special scientific investigations have been conducted, including work associated with preparing EIAs in support of site development.

Water containing radionuclides, metals and other contaminants is collected and treated within the mill effluent treatment system, consisting of collection systems, pipelines, utilidors, sumps and tanks that collect and transfer contaminated water from various facilities throughout the site. Contaminated water is pumped to the mill complex area and stored in lined reservoirs prior to treatment. Sources of contaminated water include used water from the reverse osmosis plant, seepage and runoff from ore containment areas and special waste containment areas, TMF water collection systems, groundwater collected in the mill area and run-off water from the mill terrace.

Raffinate, a waste solution from the solvent extraction circuit in the mill and contaminated water from the sources listed above, is treated with lime and acid to adjust the pH to bring about precipitation of heavy metals and other contaminants. Barium chloride is used to precipitate radium-226. Hydrogen peroxide is used to break down any organic materials that inadvertently carry over with the raffinate from the solvent extraction circuit. The treated effluent is sent to one of four monitoring ponds where the quality of water is determined prior to release to the environment. Water that does not meet release criteria is returned to the mill for re-treatment. A number of recently completed process improvements to the mill effluent treatment circuit have significantly improved the quality of treated effluent. Of note is the addition of a low pH thickener that has significantly reduced concentrations and loadings of molybdenum and selenium. A protocol for testing micro-toxicity prior to releasing treated effluent has also been implemented as one means of managing potential effects related to the presence of organic materials.

Efforts are continually being made to improve site water management by assessing key performance indicators, reviewing the overall strategy and associated risks and updating systems to improve performance and reliability where needed. Effluent water quality and downstream surface water quality are two key environmental performance indicators that are routinely monitored to assess and validate the performance of the facility. While regulatory limits have been set for specific effluent quality parameters, site-specific control levels have been established below current regulatory limits. The quality of effluent and the volume discharged are recorded and reported annually. A comprehensive environmental quality programme is carried out to assess the condition of the receiving environment with results presented annually. As well, historical results are compared to environmental assessment predictions every five years in the Status of the Environment report. Preparations for changes in water treatment, anticipated with the extension of operations, are detailed in the project description (Cameco, 2010).

Monitoring results indicate that activities associated with the Key Lake operation have had some influence on the surrounding environment. However, these changes do not extend beyond the local study area and are within the effect levels predicted and approved in previous environmental assessments.

Environmental conditions have been improving since OP mining ended and processing of McArthur River ore began. OP mining operations involved on-site activities (such as blasting, trucking and mine rock transport) that are not needed in the current milling operation. Ores from the on-site deposits had higher concentrations of several metal constituents that were treated and released to local drainage systems via the treated effluent. In addition, waste rock from the OPs, deposited on waste storage areas, contributed to some elevated metal loadings in a local drainage. The impacts of the metal-rich rock have since been mitigated by relocating select problematic waste rock to one of the OPs as well as by implementing reverse osmosis treatment of water recovered in the dewatering process prior to its release in the local drainage.

Aquatic ecology is monitored throughout the drainage systems that receive treated mill effluent and dewatering discharges. Water quality is monitored in waterbodies in these systems and components of the aquatic ecosystem, such as sediment, fish and benthic invertebrates, are sampled and evaluated every three years.

The development of the two OP mines altered the hydrogeological conditions around the site, as a large drawdown cone has developed around the pits as a direct result of mine dewatering. Although water levels in the area have increased in elevation in response to the higher water levels in the pit converted to a TMF, they remain below pre-operation levels. During the TMF operating phase the dewatering wells collect tailings supernatant, released porewater and seepage from the surrounding waste rock piles. This water has been treated by reverse osmosis since 1996, prior to discharge to the environment.

Monthly average uranium discharge data for 2010 demonstrate the reverse osmosis treatment plant's high level of performance. The annual average of 0.001 mg/L uranium is more than two orders of magnitude lower than the optimisation screening objective of 0.1 mg/L established by the national nuclear regulator to identify facilities that, while not exceeding regulatory limits, should review treatment processes to determine whether the system can be optimised or upgraded. The total 2010 annual load from this treatment system is also relatively low (6.3 kg), although slightly higher than the 2009 loading of 5.6 kg (CNSC, 2010).

The water management, treatment, monitoring and review arrangements have proved capable of maintaining aquatic impacts to within the stringent limits authorised during the licensing. With a continuation of these actions, the operator and regulatory agencies can be confident that this status will be maintained throughout the lifetime of the operation into the eventual rehabilitation and hand over (institutional control) phases.

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2.3.1. *In situ* leach (ISL)

The principle environmental advantages of ISL, compared to OP and UG mining are the minimal ground disturbance and the lack of surface waste rock piles and mine tailings that require long-term management. However, since past ISL operations have impacted groundwater resources, this mining technique will be described in this overview of managing mining impacts on water. Since previous publications (IAEA, 2001; Commonwealth of Australia, 2010) have explained in some detail modern ISL extraction methods and leading practice full life cycle management of an ISL mine, only a summary overview of the technique is presented below.

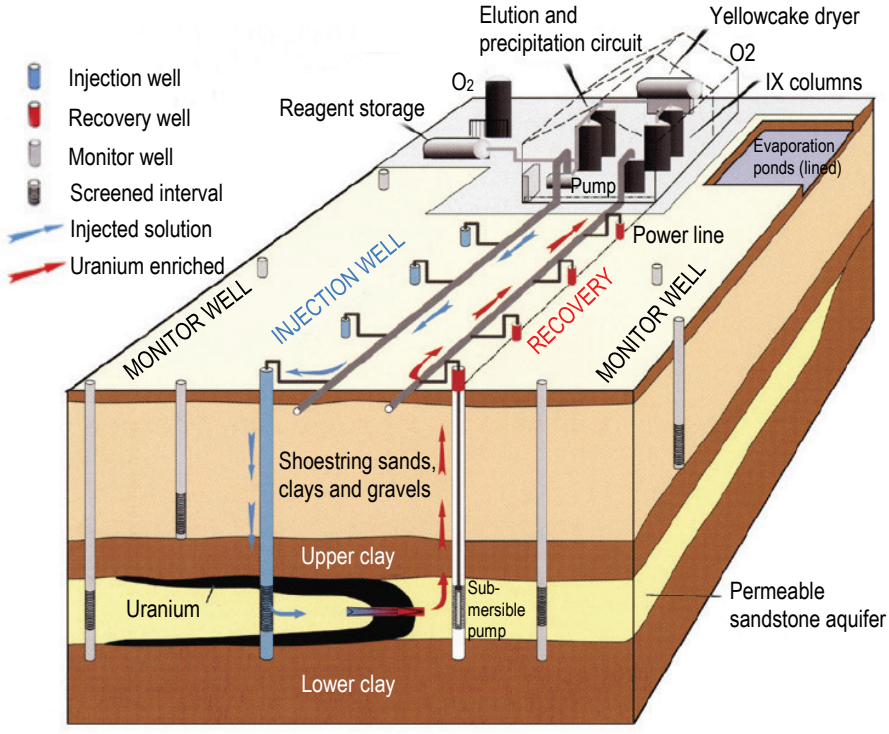
Approximately 40% of world uranium production was mined by ISL in 2010 and the share of ISL production is increasing (NEA/IAEA, 2012). ISL has become the dominant method of uranium production because capital expenditures for mine development are relatively low and mining of extensive, low-grade sandstone deposits is considered economically feasible. Kazakhstan became the world leader in uranium production in 2010 with over 95% of its production by ISL.

The main application of ISL is mining deposits in water-saturated, permeable sands. The mineralisation must be situated within sediments that effectively confine the mining solutions (commonly between impermeable clay-rich strata). The suitable leaching solution and the design of the well field for underground leaching depends on the characteristics of the host formation, mineralisation and groundwater in the mineralised aquifer and the aquifers surrounding the deposit, as discussed in some detail by the IAEA (2001). Of decisive importance to the ISL operation is whether the groundwater in the mined aquifer and neighbouring aquifers is used or can be potentially used.

The leaching of uranium from the ore is either by acid or alkaline solutions, depending on the composition of the host formation. If the carbonate content of the host rock is low, acid solutions are generally more suitable because they remove uranium more effectively. With increasing amounts of carbonate in the host formation the amount of acid needed for leaching increases, increasing costs and the attenuation time of the residual mining solution during restoration after the operation is closed. Alkaline (bicarbonate) leaching is generally used in carbonate rock where acid consumption is too high for the operation to be profitable. Recovery rates with alkaline leaching are typically lower than with acid and reaction times are longer. Various leaching enhancement methods have been used and are under development, such as the injection of oxidising agents.

In general, the ISL process involves introducing the leaching solution (lixiviant) to the deposit via an array of injection wells into the mineralised aquifer where the uranium is selectively mobilised and carried by the lixiviant to the production wells that pump it to the surface. Uranium recovery rates of 60-90% can be achieved, even in the case of low-grade (< 0.22% U) mineralisation (Commonwealth of Australia, 2010). The design of the well field and process technology are determined by the lixiviant used, the local geological structure and the techniques used to keep the lixiviant within the mined zone. Figure 2.13 depicts the basic ISL arrangement showing the ore body (permeable uranium bearing sand), injection and production (recovery) wells, flow of the leaching solution (lixiviant) and monitoring wells.

Figure 2.13. Schematic block diagram of an ISL (based on figure from Beverley EIS)



Note: Not to scale – diagrammatic only.

Source: Geoscience Australia.

After being pumped to the surface, the "pregnant" mining solution is run through a recovery plant where uranium is extracted by ion exchange or solvent extraction before the solution is injected back into the well field. To avoid unnecessarily increasing the various chemicals in the mined aquifer, the residual solutions from the ion exchange regeneration and uranium precipitation circuits should be handled separately from the leaching circuit.

The above ground elements of an ISL operation, including the uranium recovery process, waste impoundment/evaporation ponds and process controls are illustrated in the schematic of the Beverly ISL mine in Australia (Figure 2.13).

For effective control of the ISL operation, water balance modelling of the well field and plant must be conducted during operations. Extraction must be designed to minimise the risk of breaching impermeable strata and excursions of mining solutions. For example, the volume of the extracted solutions in flowing aquifers should be slightly higher than the volume injected to ensure a net inflow from the neighbouring aquifers. In stagnant (isolated) aquifer units, a neutral water balance should be maintained.

Relative aquifer pressures should be maintained (on average) during mining in well-connected aquifer systems, or restored after mining in more hydraulically isolated systems. To detect any possible excursions of mining solutions from the mining area, a rigorous monitoring programme must be established and the results made publicly available. Monitoring wells must be installed in strategic locations and water samples must be taken and analysed at regular intervals, as determined by the regulator. Off-site sampling of surface water must also be done to evaluate the potential impacts on the site and its immediate surroundings.

Environmental impact assessment (EIA)

In general, an EIA of an ISL operation follows procedures used for assessment of conventional uranium processing plants. As noted by the Commonwealth of Australia (2010), for the EIA to be a basis for planning and approval of a mining project, it should include a comprehensive characterisation of the geological, environmental and social setting in and around the proposed site, involving the proponent, the regulatory authorities and the local population, including any indigenous communities. Approval and licensing should depend on the proponent satisfying government authorities that all of the applicable potential environmental, social and economic risks have been identified and that plans for mining, environmental management, monitoring, closure and rehabilitation will result in acceptable environmental outcomes and constitute leading practice for mitigating these risks throughout the full life cycle of the mine.

An ISL mining proposal should be based on a full understanding of the hydrological, hydrogeological and hydrogeochemical features, including those indicating favourability for ISL extraction. The nature of the mining solution and the well field design should be matched to the site characteristics, particularly the minerals and groundwaters in the mineralised aquifer. Mining should not compromise groundwater in the mineralised aquifer to the extent that it cannot be remediated to meet the agreed post-mining use. At no stage should mining compromise groundwater use in the mineralised aquifer outside an agreed distance (not exceeding a few kilometres). Other aquifers present in or around the mine lease should not be affected by ISL mining.

The environmental outcomes of mine operation should be established by regulators through an iterative process involving the proponent and relevant stakeholders, in order to identify all of the appropriate environmental aspects that should be protected. Any identified impacts on the environment should meet approved outcomes.

Of particular importance is to assess whether the groundwater in the mineralised aquifer and the aquifers around it are being used or have a potential future use. Depending on the use (or planned use) and distance of use, the groundwater impacts of the residual underground leachate and the liquid waste from the surface need to be assessed. The results determine whether there is a need to remediate the aquifer containing the residual leachate and the degree of restoration required. The impact of a possible injection of the surface liquid waste also needs to be assessed in this assessment.

The mine operator should demonstrate capability through implementation of suitable management systems (including contingency plans) with adequate training and resources to ensure leading practices are implemented at the site. The impact assessment process should lead to the best option for dealing with liquid residues, either by: injection into deep aquifers containing poor quality groundwaters that have no foreseeable use; injection into former mining well fields for dispersion, attenuation and/or containment; or evaporation to solid residues and disposal on-site or in a low-level radioactive waste repository. Following closure and remediation, the site should be fit for agreed post-closure land uses and governments should not be left with any liabilities.

Radiation protection

Like at any uranium extraction plant, a radiation protection plan (RPP) must be established for ISL operations. The RPP defines the application of the basic principles of radiation protection for the specifics of ISL operation. Part of an RPP includes maintaining exposure records of the employees.

With respect to RPPs, the emphasis is, however, directed mainly on various sources of radon and dust in the entire facility (both outdoors and in the plant) and emissions of contaminated particulates, particularly with radionuclides from the uranium decay series (e.g. uranium, thorium, radon and lead).

Direct radiation measurements at the site boundary must be conducted and assessed. Radon sampling, measurement and assessment, as well as passive monitoring of the radon-222 content at the site boundary are required. Emissions of particulates and their radioactivity from the dryer/calciner scrubber exhaust must be monitored and assessed using isokinetic sampling and measurements (i.e. sampling airborne particulate matter using a collector that is designed so that the airstream entering the sampler has a velocity equal to that of the air passing the sampler).

The first generation of the ISL plants had issues with employee exposure and radioactive emissions. These were resolved with design changes employed in modern, second generation plants. The front end of the ISL process (lixiviant circulation, resin loading and extraction by a solvent, referred to as elution) is now operated as a closed system, thus reducing the potential for radon release. Emissions of radioactive particulates have been decreased by the widespread use of vacuum dryers instead of calciners that use heat to purify the product. Because vacuum dryers operate at lower temperatures than calciners, the final uranium product is more soluble, reducing the potential for long-term pulmonary retention, thereby reducing exposure. Other dryers may be used but could require additional dust extraction and collection methods to reach acceptable standards.

Radium mobilisation from the host formation can be reduced by acid leaching (if geologically feasible) due to better pH control of the lixiviant and eliminating the exchange (replacement) of radium for calcium, which is the case of alkaline leaching. Due to mobilisation of radium and subsequent evolution of radon, there are some unique radiological aspects of the ISL process compared to conventional mines.

Regarding alkaline leaching methods, observations from Wyoming (Brown, 2008) confirm that only a small part of the uranium decay products in the ore body are mobilised by the lixiviant (i.e. the selectivity of the alkaline lixiviant is high). Carbonate complexes of lead are relatively insoluble and weakly mobilised. Thorium is removed to a small extent and appears to equilibrate in the circulating lixiviant. However, mobilisation of radium is more significant, with an estimated 5-15% of the radium removed from the host formation. As a result, radon gas evolution in the lixiviant can be of radiological concern. Nonetheless, the degree of mobilisation may depend on the ISL process applied and the age of the facility.

The underground physical and geochemical conditions during ISL operation enhance the solubility of radon in the lixiviant. In the returning lixiviant the dynamically dissolved radon is carried to the surface along with uranium. Under reduced pressure conditions at the surface, radon gas is released. This happens usually in surge ponds/tanks or in the plant areas (ion exchange and elution). A detailed radiation survey is required to identify and deal with the release points.

In all cases it is essential to monitor airborne radon concentration in the plant and provide efficient ventilation in order to avoid the accumulation of radon decay products. Environmental sampling of soil, vegetation and crops (as applicable) in the vicinity of the site must be carried out and assessed for the presence of radionuclides from the uranium decay series.

Waste generation and disposal

A waste management plan must be developed during the EIA process and licensing. The decision on how to deal with the surface liquid residues of the ISL process should be based on the EIA. Should the decision be made to inject the liquid residues from the surface operations into the mined-out aquifer, similar criteria and controls should be applied as to the residual leaching solutions.

Unlike conventional mining, there are no large volumes of waste rock or mill tailings generated in the ISL process. However, the generated sludges and evaporite salts must be safely disposed of. The volume and specific activity of the wastes depends on the details of the extraction process.

Although the first generation of ISL plants generated substantially less waste than conventional mining, current ISL plants are designed to generate even less waste and emit less radioactivity than the previous generation. The typical types of wastes generated are:

- liquid waste solutions from the extraction plant (e.g. bleed solution, wasted barren solution, filter backwash);
- a small amount of solids in the form of sludge and salts;
- ion exchange residues;
- used filter media;
- chemical residues;
- conventional industrial wastes, some of them with low-level radioactivity.

Because of the specific activity of the radioactively contaminated wastes from the ISL operations, the solid waste generated in some jurisdictions is considered low-level radioactive waste (LLW) that must be disposed of in an approved waste disposal facility, according to all regulations applied to handling LLW.

Case study: Stráž pod Ralskem ISL, Czech Republic

Practices used during Cold War ISL uranium production in the Czech Republic resulted in severe impacts on important groundwater resources. These practices were the result of little or no consideration of potential environmental impacts and no prior experience with ISL technology, the lack of requirements for remediation after mining and the need to comply with demands for large production for sales to the Soviet Union. These impacts could have been reduced by investing in research, establishing remediation requirements and exercising greater care in the implementation of the technology.

Because of the large resources of sandstone-hosted uranium deposits (about 200 000 tU in total), the North Bohemian area was considered the most important region for uranium production in the Czech Republic. During the Cold War, uranium production targets were significant as all long-term military and civilian needs of the Soviet Union had to be covered, including exports to countries in Eastern Europe and elsewhere in the trading block (Fiedler and Slezák, 1992).

The ISL recovery method was initially carried out in the Stráž deposit in North Bohemia with no previous knowledge and experience to draw upon. Acid ISL pilot plant experiments were performed in 1967 and in the following year the first well field was put into operation. Uranium mineralisation is located near the base of sedimentary rocks extending to 200-250 m depth that also contain significant reservoirs of high-quality drinking water (Benes, 1992). No remediation requirements were established as the prevailing view was that natural attenuation would restore water quality after mining (i.e. with sufficient time, groundwater quality would be restored by natural processes).

The results of initial laboratory and operational testing showed that conditions for ISL extraction in the Stráž deposit were difficult, owing principally to slow reaction times (15-25 years) that could only be accelerated by increasing the concentration of the lixiviant (a mixture of sulphuric acid and nitric acid with an average concentration of about 5%). To achieve production targets, more lixiviant was injected than was withdrawn. The large volumes injected and seepage of reagents into the groundwater led to widespread contamination. The presence of a significant reservoir of high-quality drinking water above the uranium mineralisation in the Turonian aquifer (30-100 m below the surface) meant that wells had to be well engineered and constructed to avoid the loss of reagents during injection and recovery (Benes, 1992), a fact that was not fully appreciated until well after ISL extraction had begun.

Despite these circumstances, uranium extraction by ISL was expanded rapidly in 1973 after the nearby Hamr UG mine flooded and production was stopped for three years, creating a deficit in regional production requirements. Moreover, the existence of two large production complexes in close proximity – deep UG mining of the Hamr deposit (beginning in 1972) and ISL extraction of the Stráž deposit – negatively influenced one another. Although the original concept was to choose only one extraction method after pilot operations, strategic political concerns (specifically higher production targets) and "collective irresponsibility" meant that both methods of extraction were extensively developed simultaneously with increasing mutual negative effects (Fiedler and Slezák, 1992).

The ISL area is separated from the UG mine by a hydraulic barrier – a line of wells that creates an artificial pressure barrier to maintain water pressure between the two sites and prevent transport of water between the two areas. This placed conflicting demands on the local hydrology, since ISL requires saturation and UG mining requires dewatering. As a result, solutions dispersed horizontally and vertically into the surrounding groundwater aquifers (Fiedler and Slezák, 1992).

Since the Stráž ISL operation was not operated with a bleed system (less reagent is injected than withdrawn to maintain a cone of depression around the well fields), dispersion of solutions into the regional aquifers was possible. Combined with leakages associated with the hydraulic barrier, excursions of contaminants occurred over a large area. In total, over 7 500 wells were installed over an area of about 6 km^2 in the ISL operation (Vostarek, 2013) to maintain the required production levels from 1974 to 1990.

With time, it became clear that the methods chosen for mining and their implementation proved to be inappropriate and mining was scaled back in the early 1990s and stopped completely in 1995. The extensive development of both conventional UG and ISL extraction methods in a relatively small area resulted in significant unfavourable influences. Moreover, development was not accompanied by the introduction of appropriate measures and technologies to minimise environmental impacts.

Remediation activities began shortly after mining was terminated (NEA/IAEA, 1999) but are not expected to be completed until 2035. During remediation more than 3 million tonnes of contaminants are expected to be withdrawn and the total cost estimated to amount to more than CZK 40 billion (EUR 1.6 billion). During remediation, extensive monitoring, verification and modelling must be undertaken (Ekert and Mužák, 2010).

Case study: Beverley ISL, Australia

The Beverley ISL uranium mine began production in late 2000 following a lengthy period of development, study, consultation and review. A comprehensive EIA process based on a thorough understanding of local site conditions, field trials and baseline environmental data that demonstrated well field containment, led national and state governments to approve extraction using this still controversial mining technology. Ongoing environmental monitoring provides assurance that the facility is operating as planned. Decommissioning goals and plans were developed early in the process, some of which take place immediately after an active well field is shut down. These plans are reviewed periodically and the company is required to post financial assurance with the South Australian government to cover future decommissioning costs.

The Beverley uranium project is located on an arid plain some 550 km north of Adelaide in South Australia. The deposit was discovered in 1969 and total in-place resources amenable to ISL were estimated in 1998 at a minimum of 9 000 tU at a grade of 0.15% U (Heathgate, 1998). The uranium is deposited in the sands and clays of an isolated aquifer between 100 and 140 m below the surface in 3 main lenses. The Beverley aquifer is separated from the potable waters of the Great Artesian Basin aquifer by approximately 100 m of dense, highly plastic clays (Heathgate, 1997).

The development of the mine, the first ISL uranium production centre in Australia, was a lengthy process, as outlined by McKay and Mietzitis (2001) and Birch et al. (2013). Intensive drilling to define the resources was carried out through 1971 and 1972, followed by metallurgical and engineering studies to investigate the feasibility of mining the deposit as a conventional open-pit operation. However, Commonwealth government uranium policy and market influences caused the project to be postponed in June 1974.

In 1981, the South Australian Uranium Corporation acquired the deposit and began technical and environmental studies to investigate the possibility of extraction by ISL. A draft EIS for the proposed operations was released, but restrictions on the opening of new uranium mines in Australia (the “three mines” policy introduced by the Commonwealth government in 1983 that restricted development of uranium mines), together with declining uranium market prices, led to the project being postponed again in mid-1985.

In 1990, the site was acquired by Heathgate Resources Pty Ltd, an affiliate of General Atomics (United States). Following the removal of the "three mines" policy in 1996, ISL field trials were carried out in 1998 to test the viability of ISL. The draft EIS for the proposed development, released in June 1998, was assessed jointly by the Commonwealth and South Australian governments. The supplement (response document) to the EIS was released in September 1998 and in April 1999 the company received Commonwealth and state environmental clearances to develop Beverley. Construction of the ISL plant and well fields was completed and production of concentrates commenced in November 2000 with an initial annual production of about 850 tU.

The Beverley EIA process, conducted jointly by the state and Commonwealth governments, was led by the South Australian Environmental Impact Assessment Branch of Planning. In making its assessment, input was co-ordinated from a wide range of technical expertise within the state government, drew on information and expertise from a number of Commonwealth agencies and independent consultants. Input was also sought from all interested parties, including members of the public, in a comprehensive consultation process, a process repeated for extensions in 2008 and 2009 (Walker, 1999; Woods, 2011).

The extracting solution used at Beverley, is weak sulphuric acid with oxygen (or hydrogen peroxide) as the oxidising agent. The uranium is stripped from the resin into solution and precipitated using hydrogen peroxide, dewatered and dried to obtain the final product. The operational mine site covers about 500 ha, but only about 50 ha are required for the active well fields at any one time. The associated infrastructure includes a gas-fired power station, the processing plant, a small camp for workers and an airstrip (Birch et al., 2013).

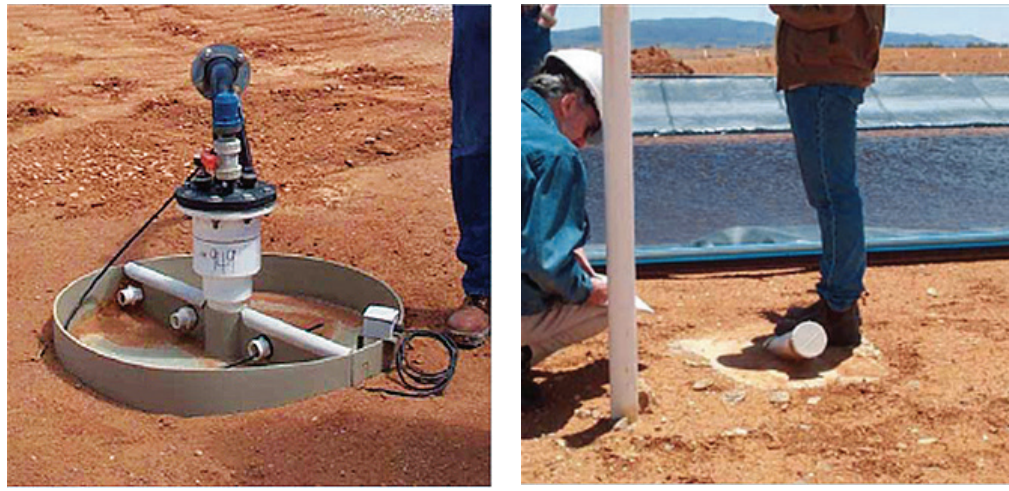
Groundwater in the mineralised zone is saline, with total dissolved solids in the range 3 000-12 000 mg/L. Prior to mining, the groundwater contained naturally occurring uranium, radium and fluoride well in excess of drinking water limits, making it unsuitable for use as potable water, agriculture or stock watering (Howles, 2000; McKay and Mietzitis, 2001). Critically, there is considered to be no potential for mining-affected water from the Beverley project to enter the underlying Great Artesian Basin aquifer (CSIRO, 2004).

As the operation depletes an area of the deposit, the well field is decommissioned, wells are sealed and capped, and the piping relocated to the next area to be exploited. The mining company is obliged, under the legislation, to leave the site in a state compatible with the final land use agreed upon with stakeholders and traditional owners of the area. This will include the treatment of wells, as well as the dismantling and removal of all unwanted infrastructure, such as the processing plant and evaporation pond (Waggitt, 2011).

The company is required to monitor soils, water and air in accordance with a programme set out in the Environmental Monitoring and Management Plan, the Radiological Management Plan and the Radiological Waste Management Plan, all of which are approved by the regulating authorities (Figure 2.14). Reporting to the authorities is carried out quarterly and annually. The cost of decommissioning and remediation of the Beverley mine site is assessed annually and the amount is kept in bond by the South Australian government (Waggitt, 2011).

Liquid wastes from operations are disposed of by re-injection into the Beverley aquifer zone in mined-out areas. Liquid wastes come from several sources: a mining solution bleed at the plant; spent solutions from the uranium precipitation process; and wash-down water and filter cleaning water. For environmental approvals to dispose of liquid waste, the company was required to demonstrate that there is no hydraulic connection between the Beverley aquifer and surrounding aquifers (Howles, 2000; McKay and Mietzitis, 2001; Jeuken et al., 2008; Woods, 2011).

Figure 2.14. Wellhead with drip tray and online detector (left), evaporation pond with leak monitoring (right) at the Beverley mine



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In 2004, the Commonwealth government approved a proposal to optimise operations to produce up to 1 272 tU per year. Heathgate Resources was granted a new uranium export permit in which the government imposed a number of conditions, including that the Beverley operations are to be carried out on the basis of a neutral water balance (i.e. the total volume of fluid injected into the aquifer from all sources must equal the total volume pumped out [NEA/IAEA, 2006]).

Since beginning operations, exploration by Heathgate Resources has led to the discovery of 3 new sandstone-hosted uranium deposits within 20 km of the Beverley mine (Märten et al., 2011). This, combined with the potential for additional discoveries suitable for ISL extraction, led the Commonwealth government to release, in 2010, a best practice guide for ISL to assist project proponents and regulators in the assessment of new ISL projects (Commonwealth of Australia, 2010; NEA/IAEA, 2012).

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2.4. Tailings

Tailings are the waste product remaining after the extraction of a valuable element from the mined ore. In extractive industries, the resultant tailings often represent the primary hazardous waste which must be managed into the very long term. Tailings management broadly encompasses the chemical and physical processes involved in the production and placement of tailings, and the development, operation and closure of the facility into which the tailings are impounded.

Tailings composition

Tailings composition depends on the mineralogy of the ore, host rock and blending materials, and on the chemical extraction process used to recover the metal from the ore. While the rate of tailings generation varies with the mill production rates, the amount of discharged tailings depends mostly on the overall production level of the mill and concentration of uranium in the feed ore, referred to as the "head grade" (i.e. a head grade of 1% U will result in 99% of the content of the parent ore directed to tailings).

Uranium extraction is generally accomplished either by acidic (e.g. sulphuric acid) or alkali (e.g. bicarbonate) leaching. The choice of acidic or alkaline reagents depends on the mineral composition of the ore. The treatment process also liberates other constituents of potential environmental concern from the parent ore, such as heavy metals. Consequently, water discharged with the tailings solids to the tailings impoundment, i.e. liquid effluent, must be removed by either evaporation or treated prior to release.

After extraction of uranium the tailings still contain some uranium (extraction never reaches 100%) and the radioactive elements of the uranium decay chain, including radium. Radium decay is responsible for the radon exhalation experienced on the tailings surface. The amount of radioactivity remaining in the tailings is to a large degree controlled by the grade of uranium ore brought to the mill for processing. Generally, approximately 85% of the total activity contained in the uranium ore is deposited in the tailings. After decay of thorium-234 and protactinium-234 radioisotopes within a few months, the activity diminishes to approximately 75% of the ore and this level of activity remains stable for more than 10 000 years.

Following the decay of thorium-230, which takes several hundred thousand years, the tailings activity decreases to a very low level and basically depends on the residual uranium radioisotopes (^{238}U and ^{234}U). The arsenic, nickel, and other heavy metals in the ore and chemicals from the extraction process are typically included in the tailings. If pyrites (a sulphide mineral) are present in the ore, the tailings have the potential to generate acidic discharge. The generation of acid in the tailings enhances the mobility and environmental availability of the contaminants present and has the potential to cause a long-lasting contaminated acidic discharge from the impoundment. In this case, chemical treatment, including neutralisation, may be required prior to tailings placement, if there is a realistic chance of contaminant release to the environment.

Tailings containment

The function of the tailings storage area/facilities during operation is to contain discharge from the processing plant, retain the solid tailings material and manage the decant or residual waters for treatment and release, as required. Upon decommissioning the containing facility is designed to isolate the tailings over the long term to minimise, through controls, the release of contaminants into the surrounding environment. A variety of different tailings containment strategies have been used, ranging from direct disposal into natural landforms such as lakes or low-lying areas, to the construction of impoundments using man-made structures such as ring dykes, valley dams and berms,

or the use of mine workings, such as mined-out OPs and UG excavations. The risk presented by the tailings containment relates to the probability of a containment failure and/or seepage from the tailings impoundment impacting the surrounding environment, particularly surface and groundwater.

Current status

In most countries it is common to require a demonstration, through an adequate and thorough risk assessment, that the mine tailings left behind once operations have ended will not adversely affect the environment by remaining stable over the long term. Today, dam design and construction is informed by several groups mandated to develop, evaluate and implement dam design standards and guidance. Most notably, the International Commission on Large Dams (ICOLD, 1928) consolidates information and shares experience on dam safety. Correspondingly, there are many national organisations worldwide focused on learning from past experiences and improving future designs.

Leading practice is to either dispose of mine tailings in a purpose-designed management facility or in a mined-out OP that has been engineered to contain and consolidate tailings in a way that isolates the material from the receiving environment long after the facility is closed, remediation has been completed and the land and monitoring responsibilities are transferred from the mining company to government. Mined-out OPs have physical stability advantages over man-made structures, require less maintenance and are not prone to physical failure. However, use for tailings disposal may preclude future mining of additional ore.

Regulatory and societal expectations

It is the expectation of society that mines and mills operate in a manner that does not negatively affect human health and the environment. For uranium mine tailings, the perceived risk is heightened by the presence of radioactive elements, despite the fact that the most significant risk arises from concentrations of heavy metals in the tailings. However, if tailings are managed properly the impact on the environment and human health is considerably lower than some societal perceptions.

Past failures of TMFs have understandably contributed to the heightened perception of risk and demonstrated that inadequate tailings management, uranium or otherwise, can have a significant environmental and health impact. Because of the political and financial risks, the standards for corporate governance at mining companies and oversight requirements on financial institutions have evolved to the point that the risks associated with TMFs must be limited to minimal health and environmental impacts by applying leading practices.

Historical trends

During the early days of mining, when environmental impacts were neither understood nor an issue of concern to the public, few governments regulated environmental aspects of mining and tailings management did not receive the necessary attention. This meant that the physical and chemical composition of the tailings was not adequately controlled and tailings were simply placed in low-lying areas, streams or lakes convenient to the processing facility. Such practices would not be approved by regulatory agencies today unless the appropriate lack of adverse impacts could be clearly demonstrated.

The most common event causing release of contaminants from constructed tailings areas has been the overtopping of containment embankments or dams due to excessive

water inflow. In this respect the most susceptible are upstream valley types of dams and impoundments that have the greatest risk of overtopping caused by receiving runoff from outside the impoundment itself. As a result, all TMFs must consider potential water inflow events and high precipitation events and plan tailings facility design and management accordingly. It is necessary to anticipate the impact of excess inflow beyond the holding capacity of the impoundment on the embankment under extreme conditions (e.g. local flooding) and the potential impact of a subsequent failure. Today, it is established practice to construct an emergency spillway that can prevent a catastrophic failure of the dam. Historically, this was not a common practice.

Development of leading practices

Man-made structures to contain tailings such as dykes, dams and berms, are designed and constructed to meet stability requirements with a reasonable margin of safety, considering:

- slope and core stability;
- material permeability;
- seismic activity;
- climate and climate change;
- potential for flooding.

TMFs are designed to isolate tailings over the very long term. To prevent transport of contaminants from the management facility, strategies are implemented to sequester contaminants through the use of:

- impermeable barriers, both natural and man-made;
- chemical isolation;
- chemical treatment;
- consolidation;
- ground and surface water bypass;
- reactive barriers;
- strategic siting.

Contaminant transport modelling tools support the design and validation of TMFs. Modelling tools support the long-term prediction of effects of contaminant transport on the receiving environment well into the future. Calibration of the models using environmental monitoring data collected during the operating period adds validity to predictions of long-term performance.

Beyond improving the design of the facilities in which tailings are stored, advancements in tailings management have focused on controlling the chemical and physical properties of tailings materials. Tailings can be “engineered” in a manner which supports quality control of the tailings material placed into the disposal facility. The preparation process for tailings together with the mode of placement, contribute to achieving long-term stability objectives. Techniques to reduce segregation of tailings by particle size and promote consolidation improve the physical stability of the tailings and lower the hydraulic conductivity, thereby reducing water flow through the tailings and their volume.

To initiate or enhance consolidation of fine tailings the use of band or base drains in the TMF and provision of an initial load in the form of an interim cover can be

undertaken. To limit the development of extensive unconsolidated fine tailings zones, the tailings discharge point can be moved periodically or managed using a multi-point discharge arrangement. Multiple spigots are small diameter pipes that feed off ring main configurations (distribution lines), which then feed off the larger-diameter main delivery lines from the plant. Discharge of tailings slurry into the tailings pond below the water level can create significantly steeper slopes (slopes in excess of 10%) than above-water deposition techniques. This means that if the distribution head or spigot is not regularly moved, differential settlement, slumping and squeezing can occur. This can damage synthetic liners particularly if the underlying material is compressible.

It is essential that in a lined impoundment using subaqueous deposition, the tailings are evenly distributed and depth measurements are recorded at regular intervals to follow whether dramatic elevation changes are being developed. Monitoring of the discharge regime and regular maintenance are necessary to ensure that tailings are being delivered in the intended quantities to appropriate areas. Using a tremie pipe (a system designed for underwater deposition, typically for pouring concrete), subaqueous deposition into the previously deposited tailings limits segregation of the coarse and fine portions of the solid tailings for improved tailings consolidation, minimising significant elevation changes. An adequate depth of water cover on the tailings will also prevent the tailings from freezing in severe winter climatic conditions (e.g. northern Canada).

Thickening tailings material is achieved by mechanical dewatering of the slurry using compression thickeners or a combination of thickeners and filter presses. Dewatering can be continued to a point where the tailings come out at the end of the pipe as a non-segregating mass of slurry. In this state, the voids in the coarse fraction of the tailings slurry are filled with the fines forming a homogeneous mix. When this mass is placed layer by layer and the thickened tailings allowed to dry to near shrinkage limit, the tailings mass becomes dilative (make wider or larger) under dynamic (vigorous) shaking, thus preventing the possibility of liquefaction. Thickened tailings have intrinsic mechanical strength which reduces the storage volume requirements and the pressure acting on the containing embankments. The tailings are generally discharged within the TMF from a topographic high point by riser towers or central ramps. Water remaining after deposition (only bleed water) and any surface runoff is collected in a pond at the toe of the pile. Typical slope angles of 1-3.5 degrees can be achieved to form a self-draining shape that is easily remediated. The first to utilise this method was Falconbridge (owner of the Kidd Creek Metallurgy Plant) in Timmins, Ontario, Canada in 1973. By using thickened tailings disposal (TTD), Falconbridge could avoid the need to raise the embankments of the TMF.

However, operating costs are higher for TTD and they have to be carefully managed in freezing cold climates, as the tailings mass and the remaining water can freeze in place. When freezing occurs, thaw back and porewater release becomes an issue during final remediation and close out. Nonetheless, there are significant advantages to TTD. Perhaps the most important in arid climates is that water is conserved and evaporation minimised. The potential for recovering high volumes of water at the plant (by the thickeners) compensates for losses associated with the transport and storage of water either at the tailings facility or in holding ponds. Groundwater contamination problems (such as seepage, spillage of process water and liquefaction after embankment breach) are practically eliminated, no large starter dams are required (which reduces capital costs), future remediation is easier (and considerably cheaper), dam/embankment stability problems are less likely to occur, management of tailings pond water becomes simple, seepage problems are minimal and pumping costs to and from the processing plant are considerably reduced. The homogeneous mix form inhibits oxygen entry into the tailings mass thus reducing acid generation in case of tailings containing sulphur. The stability of the tailings mass can be increased by adding binders (such as bentonite), thus reducing potential erosion and preventing seepage.

Case study: Helmsdorf tailings impoundment, Germany

The Helmsdorf tailings pond is one example of the extensive legacies left following Cold War uranium production in (former East) Germany. Tailings were deposited in a shallow valley adjacent to the processing plant, contained by two dams constructed of waste rock. No bottom liner for groundwater protection was installed prior to operation and little consideration was given to the potential impacts from leakage or a dam failure on communities located downstream of the impoundment. By the time processing was stopped in 1989, the tailings pond contained approximately 50 million tonnes of carbonate tailings. Remediation was costly and challenging. Environmental hazards and remediation costs could have been considerably reduced by planning for closure and remediation in advance of the commissioning and operation of the tailings storage facility.

SDAG Wismut, a Soviet-German joint stock company, managed the development and operation of uranium mines under control of the Soviet Union in former East Germany. From the 1950s through the 1980s, a total of more than 216 000 tU was produced from more than 20 deposits with very different geological settings and size (Hagen and Jakubick, 2011). The sole customer was the government of the Soviet Union. With annual production rates of as much as 7 100 tU, Wismut accounted for some 20 to 30% of world uranium production during this period.

When in production, the operator made no substantial technical or financial provisions for the closure of these large mining and processing facilities and no pre-mining baseline environmental data were collected. The priority of the time was maximising uranium production to meet military requirements during the Cold War, with little to no consideration to the costs of production, let alone post-production rehabilitation and social costs. The ore mined was generally low grade (~0.1% U) and, as a result, large amounts had to be mined and processed. Very little rehabilitation was undertaken during operations. An extensive area (100 km^2) in densely populated regions of Germany was negatively affected due to the goal of maximising production, resulting in severe environmental damage and the creation of extensive liabilities.

The Crossen mill (processing plant), established in 1950, was fed by ore from mines in the Ore Mountains and the Ronneburg district, and until 1960, from OP mines near Seelingstädt. In total, some 74 million tonnes of ore were processed and a total of 77 000 tU were produced at the site (BMWi, 2011). Wastes from the milling process were disposed as slurries in the Helmsdorf, Dänkritz I and Dänkritz II tailings impoundments. Helmsdorf was the largest of the three (Figure 2.15), containing about 90% of the total amount of tailings produced (Nelson et al., 1993).

The Helmsdorf tailings impoundment is an upstream, valley-type impoundment, created by the construction of two dams in a conveniently located shallow valley. Unsorted waste rock was used as the principal construction material in these dams (Nelson et al., 1993). Tailings deposition took place from 1958 until 1989.

After reunification of East and West Germany, remediation activities were undertaken. Since SDAG Wismut's communication policy was traditionally very restrictive and there was no interaction with the public, changes were required to effectively communicate with the public the proposed methods and remediation goals while carrying out the extensive rehabilitation work. Wismut GmbH, a uranium mine remediation company of limited liability, was created in 1991 to deal with issues connected with such activities of the former SDAG Wismut, including the institution of a proactive communication policy with the public and other stakeholders. The starting point of the new policy was clearly distinguishing "past" issues and "present" remedial activities.

Figure 2.15. Helmsdorf tailings disposal area during operations

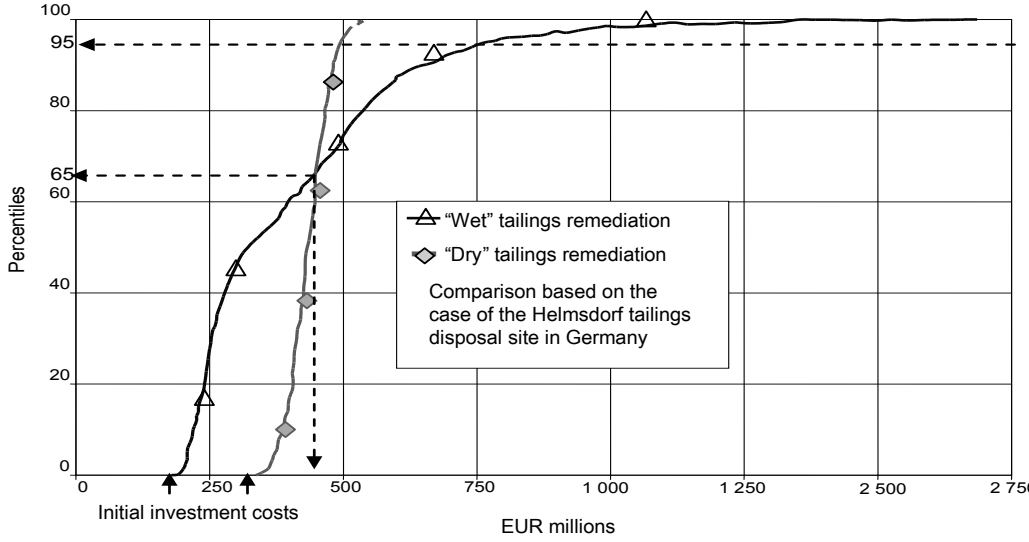


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In 1992, it was determined that the main dam (1 800 m long and 59 m high) did not meet safety standards for water retaining structures. In the case of a complete dam failure, 6 million m^3 of pond water and 15-30 million m^3 of tailings slurry could be released. These tailings contain, among other contaminants of concern, 80 tonnes of uranium and 600 tonnes of arsenic. A dam failure would have directly impacted approximately 1 000 inhabitants in the path of the slurry wave and indirectly impacted some 6 500 people due to the tailings release temporarily damming of the Mulde River. With such a failure, an area of approximately 1 000 hectares would be damaged and contaminated.

Prior to the remediation of the Helmsdorf tailings pond, a decision had to be made whether the tailings impoundment was to be turned into a lake with a controlled water table (similar to remediation of the tailings impoundments in Elliot Lake, Canada) or into a "dry" landform that fits into the existing landscape. A probabilistic risk assessment was carried out for both options to evaluate costs over the lifetime of the facility (Figure 2.16).

Figure 2.16. Estimated maintenance, repair and mitigation costs over the lifetime of the Helmsdorf tailings site to evaluate "wet" and "dry" remedial options



Source: Roberds et al., 1996.

The facility lifetime considered in the analysis was dictated by the occurrence of the most severe credible disruptive event, which in this case was the failure of the tailings dam due to an earthquake (Helmsdorf is located in a low to moderately high seismic zone). Both remedial options were considered feasible however, with increasing time the probability of rising costs for the "wet" option increased more than for the "dry" option. Although the initial investment costs of the "wet" remedial option were considerably lower, in the long term the "dry" remediation option was considered preferable in terms of safety and economics.

Both remedial options promised safe performance for up to 65% of the lifetime of the tailings. Beyond this, the initial cost advantage of the wet remediation option was lost and at 95% of the lifetime the dry remediation became more favourable (a 95% probability of safety was requested by the community located 150 m downstream of the facility). The use of the lifetime approach allowed a comparison of the overall costs of both options at the same probability level. Without using the lifetime approach, the economic comparison of the options would have been flawed.

Remediation work began in 1996 after commissioning a new water treatment plant (at a cost of some EUR 20 million). Supernatant water pumped from the tailings could then be treated as the water level is gradually lowered. Later, the exposed tailings areas were capped with a 1.5 m thick interim cover, consuming 2.9 million m^3 of waste rock, sand and gravel. By 2011, the interim cover was 98% complete, with a small residual lake remaining at the pond's deepest point. Work since 2002 has also been aimed at establishing a final contour design of an undulating landscape of hills and swales, involving slope flattening and partial excavation of embankment dams. Since 2005, contoured areas are being capped with a final 1.5 m cover of mineral soil. The plateau relief is designed to allow the discharge of surface run-off away from the tailings dump. By turning the tailings pond into a dry landform the required level of safety was achieved since the possibility of liquefaction of the tailings was pre-empted.

Contouring and final cover placement is expected to be finalised by 2017 and the reclaimed area will be used mainly for forestry. Land use will be managed and post-remedial care and maintenance will be provided. Long-term requirements include water treatment and monitoring (BMWi, 2011).

Case study: Cluff Lake tailings management area, Canada

The Cluff Lake tailings management area (TMA) is an example of a tailings facility established early in the modern era of uranium mining that employed a new approach to the tailings management strategy typical of the time. A nearby valley was chosen as the treatment and disposal site, with the tailings retained behind a dam built with an impermeable cut-off wall and a sophisticated groundwater monitoring network. This strategy was approved by the regulatory agencies following an environmental assessment and a public enquiry. As additional deposits were discovered in the immediate area of the facility and the life of the mine extended, the TMA was sequentially expanded and modified for increased tailings capacity, additional internal berms were built and the TMA was separated into a solids and a liquids area to better manage the wastes. The facility has been decommissioned and is now in the post-decommissioning monitoring phase.

The Cluff Lake mine and mill is situated in a remote area of north-western Saskatchewan, Canada. Discovery of uranium mineralisation of economic interest occurred during exploration activities in the 1960s. The initial environmental assessment for the facility's development was referred to a broader public enquiry on the expansion of uranium mining in Saskatchewan and its global implications (known as the Bayda Commission). Following the Bayda Commission and regulatory approvals, uranium

mining and milling began in 1980. Subsequent expansions of the facility to include the mining and processing of additional ore bodies were the subject of additional environmental assessments, culminating with a comprehensive study level of environmental assessment prior to receiving decommissioning licences. Unless otherwise indicated, the information presented in this case study is derived from this final environmental assessment that preceded decommissioning (CNSC, 2003).

The Cluff Lake TMA is located upstream of receiving water bodies Snake Lake and the Island Lake drainage basin. The original dam was built with an impermeable cut-off wall and contained multi-level groundwater monitoring piezometers, temperature sensors and ground movement monitors. Two additional dams were built in 1982 during the first extension of operations and a dike was constructed to divide the tailings pond into a solids pond and a liquids pond in 1984. In 1986, a berm was constructed across the solids area to segregate the tailings produced during the first phase of the operation. To optimise the TMA area, internal berms were constructed in the 1990s to further segregate tailings and improve existing storage capacities. In 1999 and 2000, diversion ditches were constructed on the two sides of the facility to divert clean surface water around the TMA.

Milling operations were ended in 2002. During the operational life of the Cluff Lake mill, all tailings and contaminated water generated at the site were transferred to the TMA for disposal and treatment. The TMA includes primary and secondary water treatment systems and freshwater diversion ditches. The main retaining dam that defines the downslope extent of the TMA is approximately 1.24 km long and has a maximum height of 6.5 m. Geotechnical evaluations of the dam determined that it is stable, structurally sound and fully meets all design specifications.

The containment and decantation areas were divided into various ponds by using internal berms and dykes. These ponds were used to separate coarse and fine tailings, increase storage capacity and facilitate decantation. During milling operations, tailings were discharged into specific pond areas. Tailings decant liquid, mill tailings thickener raffinate (liquid remaining after solvent extraction in the mill), and mine water were fed to the primary treatment plant for radium-226 precipitation. After retention in two settling ponds to increase precipitate settling, final treatment and discharge to lined settling ponds preceded final discharge to a local creek at the outlet of Snake Lake. This lake is upstream of the discharge point and receives no direct effluent discharge, although it does receive seepage of partially treated tailings water from the liquids pond and seepage of tailings porewater under the main dam. At the time of decommissioning, the entire storage area contained approximately 2.6 million m^3 of tailings.

In 1999, two of the four settling ponds were removed from service and partially reclaimed. Diversion ditches were constructed in 1999 and 2000 to direct uncontaminated water around the TMA to Snake Lake. The diversion ditches were designed to ensure that area runoff from a probable maximum precipitation event would safely be diverted around the TMA.

In 2001 and 2003, a 1 m till levelling course was placed over the tailings storage areas to minimise radiological hazards and dust emissions, as well as to promote tailings consolidation. The groundwater between the TMA and Snake Lake has been minimally impacted as a result of seepage from the tailings area and liquids pond. Increases in major ions, trace metals and radionuclides have been observed, but are within the design parameters of the structure. A comparison of recent water quality to pre-operational data indicates increased major ion concentrations in water quality in Snake Lake, as predicted in the environmental assessment.

As predicted, the 20 years of treated effluent release and the associated reagent and contaminant loadings to the first lake downstream in the mixing zone (Island Lake) have resulted in measurable impacts on water and sediment quality, as well as aquatic ecology (changes in the zooplankton, benthic macroinvertebrates and fish communities have been observed).

Despite these issues, the environmental assessment concluded that the decommissioning of the Cluff Lake Project will not have any significant adverse effects beyond Island Lake. Although some degradation in groundwater quality in the mining areas is anticipated, it will not adversely affect existing and potential reasonable use of the groundwater. Additional effects are also predicted for Island Lake where effluent discharges from the water treatment systems over the 23-year operating life have resulted in increased concentrations of key contaminants (e.g. uranium, molybdenum and selenium) that may pose a risk to non-human biota. These potential adverse effects are not considered significant because they are moderate in magnitude, restricted to local populations in Island Lake and reversible, with substantial recovery expected in the first 50 to 100 years (Figure 2.17).

Figure 2.17. Cluff Lake TMA prior to decommissioning (left) and (right) after decommissioning and re-vegetation



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Case study: McClean Lake tailings management facility (TMF), Canada

The TMF at the McClean Lake facility is an example of leading practice in tailings management. In addition to the typical challenges of long-term tailings management, the high-grade uranium ore destined for processing has high levels of arsenic and other contaminants of concern. Safe and long-term treatment of tailings produced from processing this type of ore required extensive laboratory testing and regulatory review, combined with the construction of an engineered facility for tailings disposal. Although this site-specific technology is not directly transferable to other uranium mines and mills, the case study is included to illustrate how even the most challenging uranium ores can be processed and the wastes safely disposed when all the issues are understood and addressed in the planning and design stage and the performance of the TMF assessed by monitoring throughout its operational lifetime.

The TMF at the McClean Lake operation has been continuously operated by Areva Canada since first tailings were placed in June 1999. Over the operational period, the TMF has received tailings prepared from the processing of ore from five uranium deposits developed on the McClean Lake site (JEB, Sue C, Sue A, Sue E and Sue B OP mines). Arsenic is the major contaminant of concern in the tailings (Rinas et al., 2010) and the range of arsenic content measured in these ore bodies has spanned nearly two orders of magnitude (0.2 mg/g to 20 mg/g). The tailings management strategy used at McClean Lake and the JEB TMF have been described as a leading practice in uranium tailings management primarily because:

- A detailed assessment of tailings management options was developed well before milling began that included laboratory research and development by the

proponent (Frey et al., 2010), an intensive public EIA process and a thorough regulatory review at each licensing step, all of which fed into the final design characteristics.

- The tailings are manufactured through the tailings preparation process so that the geochemistry of the tailings in the disposal facility provides long-term control over the release of constituents of concern.
- Hydrodynamic containment is provided during the operating period.
- A hydraulic conductivity contrast is established between the tailings and the surrounding host rock so that groundwater will preferentially flow around the tailings in the long term.

Overall, the TMF has been designed to minimise the migration of soluble contaminants of concern from the facility to the receiving environment during the operating and post-decommissioning periods through passive physical containment and geochemical controls.

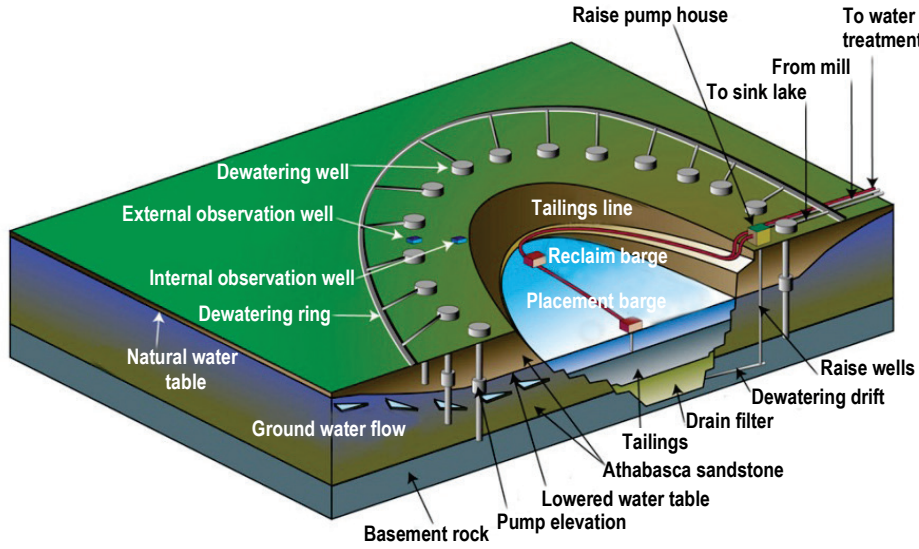
Key features of the TMF are designed to:

- Ensure hydraulic containment of tailings porewater during the operating period (40-50 years), a ring of dewatering wells has been installed around the edge of the deposition pit (mined-out JEB OP). The submersible pumps in these wells are located at a fixed elevation, slightly above the desired pond level to intercept clean groundwater before it enters the TMF (Figure 2.18).
- Monitor groundwater levels, four external observation wells are installed within the ring. In addition, four internal monitoring wells are installed between the dewatering well ring and the pit.
- Collect tailings porewater while containing the tailings solids above the filter using a base drain and graded filter package constructed of sand and crushed rock at the base of the TMF, thereby enhancing tailings consolidation by promoting dissipation of excess porewater pressure within the tailings mass. Water is removed from the base drain and pumped to surface through a dewatering drift and raise system for recycle or treatment.
- Transport tailings by lines from the mill that run down the TMF ramp and onto a floating walkway leading to the placement barge. The discharge pipe is suspended below the barge and the tailings are placed within the previously placed tailings using a shallow injection tremie method, as outlined above.
- Use a reclaim water barge to precisely control the pond water level by returning excess water inflow not captured by the dewatering wells back to the mill.

Groundwater flowing through the TMF area provides the mechanism for interaction with the receiving environment, potentially impacting the water quality of several local lakes and streams (Figure 2.19). Soluble contaminants of concern present in the tailings porewater can potentially be transported to the surface environment through the groundwater pathways. However, the interaction with the surface receiving environment is exceedingly slow, with concentrations of contaminants of concern requiring thousands of years into the post-decommissioning period to reach maximum values in the receiving water bodies. This long-term period notwithstanding, it is important to ensure that these maximum end point concentrations remain within acceptable levels defined by surface water quality standards.

Environmental protection for the post-decommissioning period relies on passive techniques, established during operations, to minimise the release of potential contaminants of concern for the long term.

Figure 2.18. Key features of the McClean Lake TMF



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Figure 2.19. Aerial view of McClean Lake (left) TMF (in background) and surface view (right) of TMF



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Action levels and monitoring programmes have been implemented for the production of tailings at the mill and for tailings following placement in the TMF to ensure that arsenic concentrations would remain satisfactory in the receptor water bodies following decommissioning of the TMF. A specific monitoring and research programme, the Tailings Optimization and Validation Program (TOVP), was accepted following rigorous review by regulatory agencies as the method by which the operator would assess and optimise tailings performance. The principle purpose of the TOVP is to ensure that the geotechnical and geochemical conditions in the TMF, necessary for functional passive controls on the release of contaminants of concern to the surface aquatic environment following decommissioning, are being established during the operating period. The TOVP programme consists of an ongoing technical investigation and scientific research to verify that key design parameters which characterise the placed tailings are being established as the operation progresses and will be in place for the post-decommissioning period to provide long-term environmental protection. A key design parameter for production tailings discharged from the mill is the porewater concentration of arsenic. For the first decade of operation, the arsenic content in the ore

feeding the mill has ranged over two orders of magnitude. Despite the large range in treatment requirements, the arsenic concentration in the discharged tailings porewater has consistently achieved the predicted operational performance, verifying the effectiveness and robustness of the tailings preparation process for the control of soluble arsenic concentration.

The key geotechnical design parameter for post-closure performance of the TMF is the hydraulic conductivity of the placed tailings. Geotechnical studies have confirmed the ability of tailings sediments, placed adjacent to the TMF walls, to consolidate and provide sufficiently low hydraulic conductivity values, in relation to those associated with the surrounding sandstone host rock, and to be suitable for the control of groundwater flow through the decommissioned facility. Solute transport analyses are conducted, incorporating all currently available geotechnical and geochemical information, using a source term model to predict concentrations of potential constituents of concern in all receiving waters. These are demonstrated as sufficiently low to ensure adequate environmental protection in the long term.

In summary, AREVA has been monitoring and studying the tailings produced at the JEB mill for over ten years. In that time, AREVA has not only validated predictions of tailings performance in physical and chemical terms, it has advanced the state of science for uranium tailings geochemistry.

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2.5. Waste rock

Much of the material excavated during the mining of any mineral, including uranium, is of no commercial value and considered a waste product. The ratio of the waste rock to ore production, referred to as the stripping ratio, is a key factor in the economic feasibility of any mine. Stripping ratios vary with mine design. OP mine stripping ratios can be very large, e.g. 40:1 or more; UG mine stripping ratios are much lower and can be less than 1:1 and ISL extraction produces virtually no waste rock.

Waste rock can be classified as either clean or problematic. In fact, with good characterisation and controls, a significant portion of the clean waste rock can be stockpiled and readily used for construction purposes, such as in roadways and for erosion protection around stream crossings. Waste rock, without enough of the mineral of interest to be of commercial value, may however contain trace quantities of the target mineral, or other minerals, which have the potential to adversely impact the environment. The presence of sulphate or carbonate minerals is of particular concern. Weathering of waste rock containing such minerals has the potential to alter the chemical properties of water which can have a direct detrimental effect on the environment through acidification and by the potential to mobilise other heavy metals in the waste rock or the environment. The flow of acidified water from mine sites is generally referred to as acid rock (or mine) drainage (ARD or AMD). These issues are common to all mining activities. Uranium mining, however, has the additional concern of radioactive elements in its waste material. Hence, the mobility and effects of radionuclides in the environment must also be considered in the management of mine rock.

Current status

The properties of mine waste rock are an important consideration of planning for any type of modern mine, uranium or otherwise. Waste rock is characterised through sampling and laboratory testing to understand the potential for acid generation and leaching of trace elements. Laboratory testing simulates the effects of weathering on mine rock, evaluates the potential for both acid generation from sulphate minerals and neutralising capability from carbonates and determines the leachability of trace metals. Mine rock management plans are developed and the potential effects on the environment are considered during the EIA and licensing phases. Mine rock management plans include strategies to segregate benign (clean) mine rock from potentially problematic mine rock.

Regulatory and societal expectations

In the past, limited consideration of the chemical composition of mine rock was given before its placement in waste piles or its use as mine backfill or construction materials. As a consequence, a legacy of ARD and heavy metal leaching from mine sites around the world was created. In addition, problematic waste rock has been removed from mine sites and inappropriately used elsewhere.

Given this history, it is the expectation today that mines will effectively and manage waste rock, particularly problematic waste rock.

Historical trends

Several techniques have been developed to minimise undesirable environmental effects caused by ARD and leaching of metals. Placing problematic rock underwater is often an effective way to slow oxidation and contaminant release. Neutralisation techniques, using lime or carbonate additions, as well as precipitation techniques, are also employed. *In situ* passive techniques, such as constructed wetlands and reactive barriers to precipitate metals, are also in common use at mine sites, including uranium, to intercept and treat outflows.

The International Network on Acid Prevention (INAP) is an organisation of international mining companies dedicated to reducing liabilities associated with sulphide mine materials. INAP sponsored the development of the Global Acid Rock Drainage (GARD) Guide (INAP, 2009), a technical document developed to support scientists and engineers dealing with the prediction, prevention and management of drainage produced from sulphide mine materials, including associated metal leaching.

The International Council on Mining and Metals (ICMM) was established to improve sustainable development performance in the mining and metals industry. ICMM provides advice through its guidance and best management practice documents on sustainable development aspects in mining, including mine rock management and mine closure planning (ICMM, 2006).

Development of leading practices

In many countries, nuclear regulatory agencies provide oversight to the nuclear aspects of uranium mine development. Mine rock containing radionuclide concentrations above certain thresholds receives a classification of naturally occurring radioactive material (NORM) and in some jurisdictions is categorised as a radioactive waste. The IAEA provides standards and guidance to the nuclear industry, including uranium mining. Specific guidance relating to mine wastes is provided by the Safety Guide Series (IAEA, 2002).

Mine rock management remains an issue of key importance in developing a mine and planning for its eventual closure. International industry and governmental agencies and associations have collaboratively researched, evaluated and developed best practices in the management of these materials.

Case study: Poços de Caldas waste rock disposal, Brazil

This case study illustrates the impacts and long-term problems that arise when waste rock disposal is neither carefully planned nor the waste characterised and treated accordingly during operations. Simply depositing the material at a convenient, nearby location without fully understanding its geochemical properties or long-term management challenges can lead to long-term problems. This is not a unique example, as numerous mines around the globe in the early phase of uranium mining did not investigate or fully understand the impacts that their waste management options could cause and, as a result, legacy issues were created by not treating problematic waste rock accordingly.

The Poços de Caldas uranium mining and milling facility, the first in Brazil, was developed by the national government to provide uranium for its nuclear programme. Situated on a volcanic plateau in south-eastern Brazil, the project, initiated in 1974, resulted in the production of a total of 1 097 tU in the 1980s and 1990s. The mining practices employed at the time resulted in a number of environmental impacts of

particular importance since water from two rivers whose watershed boundaries include the mining and milling site are intensively used downstream for irrigating crops (e.g. potatoes, corn, brown beans and carrots), watering livestock and fishing (NEA/IAEA, 1999). This case study focuses on one of the impacts of the site; ARD from waste rock piles produced during excavation of the large (2 km^2) OP mine.

Removal of the overburden during development and mining of the 300 m deep, 1.2 km diameter OP mine produced 5 significant waste rock piles with a combined volume of 45 million m^3 and a total weight of 110 million tonnes. One of the largest piles was built in a valley near a stream bed (Figure 2.20), using a construction method known as end-dumping (i.e. the waste rock was simply dumped from trucks directly into the stream bed valley). Criteria used for waste rock disposal site selection were limited to the stability of the substrate and the economics of moving the waste rock (distance and elevation change) in order to minimise costs. The only preparations made in the bottom of the valley selected for deposition of the waste rock were the construction of a compacted soil liner and the excavation of drains to facilitate the run-off of infiltrating water (average annual precipitation in the area is 1.7 m). No testing or sorting of the waste rock was undertaken and no consideration was given to mine closure costs and challenges at the time that the mine was developed.

Figure 2.20. Acid generating waste rock pile, Poços de Caldas



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Since the waste rock contains pyrite, oxidation leads to the drainage of sulphuric acid-rich water and is the driving force for the release of contaminants of concern, such as iron, manganese, radium, radioisotopes (^{210}Pb and ^{210}Po) and uranium, from two of the larger waste rock piles. As a result, collection of drainage water in holding ponds, pumping to the mine pit and treatment to neutralise the water and remove contaminants is required on an ongoing basis. Solids collected in this process are deposited in the tailings pond before the treated overflow is released to the environment. The neutralised overflow must comply with the authorised levels established by the regulatory authority before being released.

The treatment of acidic water pumped from the holding pond results in annual costs amounting to USD 1 to 1.2 million. A total of 145 000 tonnes of precipitate recovered from the treatment of ARD has been deposited in the waste dam and mine pit through August 2012. It is recognised that the current collection and treatment option is not a viable permanent solution (NEA/IAEA, 2002) and activities are underway to identify and implement appropriate remediation measures.

Case study: McClean Lake mine rock segregation, Canada

Waste rock management at the McClean Lake operation demonstrates how a leading practice waste rock management plan is developed and implemented. A detailed waste rock management programme completed prior to the beginning of mining following studies by the mine operator and reviews during the EIA and licensing led to the implementation of procedures that result in the environmentally sound treatment, use and long-term disposal of waste rock. The McClean Lake waste rock management programme is an example of a modern and effective programme, based on the historical lessons learned and the application of sound science and long-term site management principles.

At the McClean Lake operation, the waste rock management programme consists of several important components, including waste rock characterisation, segregation and the development of disposal options (Government of Canada, 2011). Waste rock is generally categorised according to its origin and nature. Clean waste rock refers to mined bedrock with low contaminant levels and no acid generating potential. Potentially problematic waste rock refers to material with significant contaminant concentration or acid generating potential which requires special management to minimise environmental impacts. The classification of clean and potentially problematic waste, followed by the development of a waste rock segregation programme, will vary on a project-by-project basis and is dependent on the results of the waste rock characterisation programme as well as the site geology.

Environmentally benign clean waste rock is managed in surface stockpiles or can be used for construction purposes (e.g. roads, berms, rip rap). Problematic waste rock, which has the potential to leach contaminants into ground and surface waters, is managed by placing it into a mined-out OP which is subsequently flooded. Subaqueous placement of the waste rock protects the material from oxidation and resultant transport of contaminants.

Lining of the mined-out pits used to store problematic waste rock with low permeability material has not been necessary to protect the surrounding environment at the McClean Lake site. Sub-aqueous deposition of the problematic rock maintains constituents of concern in reduced mineral forms limiting the pore water concentration of contaminants. Low magnitude source concentrations coupled with the site's hydrogeologic conditions result in predicted peak concentrations of contaminants of concern in neighbouring surface water receptors that meet environmental quality criteria in perpetuity.

Segregation of problematic waste rock at the McClean Lake operation is one component of the overall waste rock management strategy. Waste rock segregation procedures are developed to ensure that potentially problematic waste rock and benign waste rock are effectively categorised, separated and transported to the appropriate disposal area.

Clean and problematic waste rock has been effectively segregated during the mining of the JEB, Sue C, and Sue E pits at the McClean Lake operation based on a number of techniques, such as:

- systematic radiometric scanning of blast hole cuttings in clean waste zones to detect anomalous radioactivity levels;
- radiometric probing of blast holes in ore zones to define ore and waste boundaries;
- radiometric scanning of working faces during excavation to confirm blast hole scanning and probing results;

- overhead scanning of waste rock in the proximity of problematic waste or ore once loaded onto trucks (Figure 2.21);
- daily inspection through scanning of the clean waste rock disposal area to ensure that no problematic waste or ore was inadvertently placed;
- systematic sampling to assess the acid generating potential of clean waste rock.

Operational procedures have been developed for the above methods. For all major projects at the McClean Lake operation, the uranium content of the waste rock has been estimated in the field using radiometric techniques. Drill cutting assay results are then used to confirm the field predictions. This is the main segregation procedure used at the site.

Figure 2.21. Overhead scanning of mined rock to classify ore and segregate potentially problematic waste rock for appropriate disposal, McClean Lake



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An additional segregation procedure using X-ray fluorescence (XRF) technology has been recently implemented. XRF technology is generally accepted as a quantitative screening tool for environmental investigations and industrial site clean-up activities. XRF technology was first used at the McClean Lake operation for the Sue E project. The XRF is particularly useful for the determination of arsenic content in waste rock during mining, but other constituents of concern such as nickel, lead and uranium can be measured as well.

Samples of cuttings from the Sue E project were sent to an external laboratory to verify the performance of the XRF unit. Results showed a good correlation between arsenic and lead results. The XRF tends to overestimate the content of nickel and uranium and is therefore conservative. Overall, the results from the Sue E project have shown that the XRF is an effective field segregation tool.

For the Sue E mining project, a total of 7 959 861 m^3 of material was excavated, of which 205 344 m^3 was ore (i.e. a stripping ratio of 39:1). Of the waste rock, 2 437 822 m^3 was segregated as potentially problematic waste, placed in the mined-out Sue C pit and subsequently flooded. Clean waste amounted to 4 619 031 m^3 and was stored on the

surface. Characterisation of the waste rock stored on the surface demonstrates it as comparable to the surrounding sandstone.

Overall, during the course of mining 696 196 m^3 of ore, a total of 27 499 247 m^3 of material has been excavated from 5 open-pit mines at McClean Lake. A total of 4 192 216 m^3 (15%) has been segregated during mine operations as potentially problematic, and placed into mined-out pits to prevent oxidation and contaminant release to the environment.

Future projects are being designed with waste rock management and segregation in mind. The mine operator (AREVA Resources Canada) is committed to continual improvement of waste rock management procedures, including waste rock segregation. Proper management of problematic rock during the mining period will minimise environmental effects over the long term.

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Chapter 3. Modern life cycle parameters

As the regulatory environment evolved and the industry adapted and developed innovations to meet emerging legal requirements, a number of parameters have been introduced in leading practice operations that were seldom, if ever, used during the mine life cycle in the early stages of the industry. These additional aspects of mine development, operation and closure are crucial to managing the health and safety of the operations. Through the implementation of these mine life cycle parameters and regulatory requirements, uranium mining has become a leader in safety and environmental management.

This chapter provides an overview of nine modern life cycle aspects, outlines the importance of each to mine management and, where practical, provides a case study of a leading practice to illustrate the significance of the particular parameter.

3.1. Public consultation

Through historic construction and operating practices, combined with a general lack of effective remediation, uranium mining has come to be viewed negatively by many members of the public. Contaminated legacy sites resulting from these poor past practices present an additional challenge to proponents of any new uranium mine development. In addition, compared to other types of mines, there is a general fear of radiation that uranium miners have to manage.

However, all parties working closely together over the last decades have helped to better manage and mitigate potential negative impacts of mining. Improving public information efforts and consultation with stakeholders allows industry to better counter any unfounded concerns or fears about the regulation and management of radiation and its impact on workers, the public and the environment. An effective public consultation process invokes a dialogue with the public and other interested parties to take into account questions, views, concerns and opinions. This is not just an information programme that simply flows outward. Rather, it is a two-way process that actively encourages and documents the questions and answers that arise. The public is a valuable resource to proponent and regulatory agencies that should be treated accordingly. Public knowledge and support will facilitate the timely review and licensing of new mines. Public fear and resistance will do just the opposite.

In the early planning stages of any new mine project, the company must identify their target audience. From that, a public consultation programme is drafted and implemented. In fact, at an early stage both the proponent and the regulators must identify members of the public, any special interest groups and non-profit organisations that may be affected by a proposed project or who may have an interest in a project. From the list of stakeholders the required level and frequency of consultation must be determined for each phase of the project life history. During the environmental assessment and licence hearing process, the public and target groups can participate in one or more of the following activities:

- proponent-led public consultation sessions or meetings in the project area;
- regulator-led public consultation sessions;
- public licence hearing sessions.

In countries with leading practice uranium mines, public consultation is a requirement in the development of any mine, from the early stages of a proposal through the licensing steps, including the operational stage when monitoring data is made publicly available and the mining companies and regulators are prepared to discuss results with the public and other interested stakeholders. Both the IAEA (2010) and WNA (2006) recognise the importance of public consultation and stakeholder involvement as a crucial component of obtaining and maintaining a social licence to conduct mining. The dissemination of factual information on the operation and the willingness to discuss operational aspects with the interested public are key components of social responsibility for leading practice uranium mining companies. Since the stakeholders are likely to consist of an extensive group of individuals, businesses and organisations with vastly different skill sets, technical abilities and, most importantly, expectations, specialised skills and resources are required to do this effectively.

Co-operative work among operators, contractors and regulators, combined with open two-way communication with the public, are essential elements of the successful management of radiation, health and safety, waste and environmental issues. The public, in particular local inhabitants and traditional aboriginal residents (when present), have a vested interest in the land and a right to know what is being proposed in their neighbourhood and, if approved, how it is operating, when and how it will be closed and decommissioned and what condition the land will be left in afterwards.

Because of the significance of public consultation in the success of leading practice operations, a number of government- and industry-driven initiatives have developed in recent years to ensure that the public is provided with the opportunity to be well informed with factual information on activities undertaken at the site.

For example, the Commonwealth Government of Australia in 1996 formed the Uranium Council to contribute to the progressive development of uranium exploration, mining, milling and export industry (DRET, n.d.). The council is an industry-led forum which includes participation from Australian government agencies with an interest in, or responsibility for, uranium mining. This includes state and Northern Territory government regulators, uranium exploration and mining companies and the Northern Land Council, an independent statutory authority that is responsible for assisting Aboriginal peoples in the Top End of the Northern Territory to acquire and manage their traditional lands and sea. Included in its wide ranging mandate is the development of principles and guidelines for public engagement and facilitating the provision of information on uranium to indigenous communities.

There are also a number of regional-based forums as well as Australia-wide forums that bring together government agencies, companies and non-government organisations to enhance communication between interested parties and increase transparency of government and industry practices. One example is the Alligator Rivers Region Advisory Committee (ARRAC, n.d.) established under the Australian government's Environment Protection (Alligator Rivers Region) Act (1978). The ARRAC is a stakeholder forum for information exchange and policy consultation in relation to the effects of uranium mining on the Alligator Rivers environment in the Northern Territory that hosts the active Ranger and former Nabarlek modern era uranium mines, numerous small legacy mines, several prospective mines and much exploration interest. Public disclosure of environmental performance data through the ARRAC is an important means of enhancing transparency and trust between relevant stakeholder organisations, and through this, providing assurance to the broader community that the environment remains protected from uranium mining-related impacts.

Stakeholder organisations provide information reports at each ARRAC meeting to assist knowledge sharing and reduce the potential for misinformation. These reports usually include a summary and interpretation of monitoring data and outcomes of audit and assessment activity by the Supervising Scientist Division, periodic environmental

reports from mining companies and updates on exploration activities in the region. The ARRAC meets twice a year.

In Canada, public consultation is an integral part of the environmental assessment process and the staged licensing process of the national nuclear regulator, the Canadian Nuclear Safety Commission (CNSC, n.d.). The CNSC welcomes public participation in several aspects of its activities and offers the opportunity for members of the public, Aboriginal peoples and other stakeholders to request funding from the CNSC to participate in its regulatory process.

The Chamber of Mines Uranium Institute was established to uphold mining practices in Namibia to the highest standards, to observe international conventions and to ensure positive development of Namibia's reputation as a mining nation. In 2007, the Uranium Stewardship Committee was set up within this framework to among other things maintain stakeholder and public confidence in the industry. The Namibia Uranium Institute (n.d.) aims to be a reliable source of energy, knowledge and support to continuously improve health, environment and radiation safety in the industry. Included in its strategic aims is a communication programme that engages practitioners and stakeholders.

In the United States, although the NRC does not regulate and license conventional mines (these are regulated by the Department of the Interior), it does so for uranium recovery facilities, including conventional mills and ISL operations. The NRC has a long standing practice of conducting regulatory responsibilities in an open manner, keeping the public informed of its activities through public consultation. Public meetings are held relating to operating facilities, licence applications for new facilities, expansions, renewals and decommissioning (NRC, n.d.). Annual uranium recovery workshops with the National Mining Association are open to the public and an outreach strategy for federally recognised Indian tribes that may be interested in or affected by mining operations.

Case study: Talvivaara uranium recovery plant, Finland

The case study illustrates the challenges associated with developing and carrying out an effective public consultation campaign. These challenges are compounded by the depth of public mistrust and misunderstandings concerning radiation and uranium. An effective two-way public consultation is required to gain public acceptance of any uranium mining activity and, through its experience in this activity, Talvivaara notes that it is best started very early on in the process and should begin by conferring with other proponents and organisations experienced in consultative processes in the nuclear fuel cycle.

The Talvivaara Mining Company Plc. operates the largest sulphidic nickel ore deposit in Europe in Sotkamo, Finland. The ore is very low grade, containing leachable nickel, zinc, copper, cobalt, manganese and uranium that can be removed from the ore by bioheapleaching, with hydrogen sulphide used to recover metals from the leaching solution. Neither manganese nor uranium was recovered when the mine began operations.

The pregnant solution obtained from the leaching process contains on average 17 ppm uranium (0.0017% U), most of which ends up in gypsum waste, although some goes partly to the nickel sulphide product. Following a breakthrough in the recovery process, Talvivaara expects to produce up to 500 tU annually through the addition of a uranium recovery circuit. As Talvivaara would be the first mine producing uranium in Finland on a commercial scale, the proposal attracted nationwide and some international attention.

The following account is based on input from Vanhanen (2012). When Talvivaara announced its intention to recover uranium early 2010, it had already tried to identify the social repercussions and main concerns of local interest groups during preliminary planning. Even before the environmental impact report was released, Talvivaara had held several face-to-face meetings with local interest groups and two nationwide seminars to inform stakeholders and give the local population a forum to voice questions and concerns. During these events people were invited to join an email group in order to obtain real-time information on the planning and permitting process.

Since uranium recovery in this case did not require additional land use outside the existing mine area, this aspect was not an issue. However, the possibility of dispersing dust or liquid waste containing uranium troubled many local residents. Berries and mushrooms are a significant source of income and companies as well as most households collect berries for personal use. Hunting elk in the area around the mine is also practised. Possible contamination of local food sources was thus perceived as potentially affecting the local population.

In addition to meetings, Talvivaara mailed 24 000 copies of a short version of the environmental impact report to households in the region and the full version was made available to any interested party. A telephone survey conducted just after the environmental impact report was announced showed that over half of the 325 local households surveyed were opposed to uranium production. A similar survey done with companies in the tourism sector revealed concerns that the region's image would be tarnished and revenue would be lost if uranium was produced.

During the environmental permitting process, Talvivaara organised 16 local meetings with all interested parties, 3 interest group panels and several press conferences. Over 100 interviews and newspaper articles were produced and the company kept in constant two-way communication with the authorities. Altogether this resulted in over ten person-years of work. Despite these efforts, several areas were identified where communication could have been improved.

Talvivaara took part in organising two panel discussions about uranium and mining, one which was webcasted and remains available. Included in these panel discussions were representatives from the national nuclear regulator, local authorities, a specialist on uranium safety, a member of Finnish parliament, an expert on uranium ores and representatives from non-government organisations opposed to uranium recovery.

Talvivaara received 27 comments or complaints on the environmental permit application, with over 60% coming from private citizens and non-government organisations. Comments from authorities and local municipalities were more positive and asked mainly for clarification of parts of the application, whereas private citizens demanded more strict emission limits, including closing down the entire mine.

During meetings with the local population, the biggest challenge was finding a common language. The level of education of the participants varied widely and while some people were asking precise technical questions, the majority had trouble understanding that uranium is a natural part of the ore already utilised and removing it during processing would not increase the level of radiation.

Participation by the Finnish Radiation and Nuclear Safety Authority (STUK), the national authority overseeing Talvivaara's operations once uranium production begins, was critical in obtaining trust. Officials from STUK answered many of the common questions and were seen as providing impartial knowledge. Talvivaara also brought in independent experts to talk about the nature of the ore and the process of environmental permitting.

The greatest challenge in the overall process was establishing effective communication with those requesting information. After sending 24 000 copies of the environmental impact report to locals, the company had no way of knowing how many

people actually read the document. The same could be said for the web pages and interviews in newspapers.

While organising meetings with the local population proved to be a lot of work, it is also the surest way to hear what locals have to say and define the issues causing the greatest concern. In addition to public meetings, Talvivaara organised 2 open house events, with about 3 500 visitors in total taking part. Follow-up interview campaigns showed improved acceptance of uranium extraction by those who had visited the mine site. People that had not taken part in the mine tours were in general less accepting of the activity.

Questions could also have been answered better. Initially, Talvivaara had no means of establishing easy contact outside of public meetings. It was later shown that a blog, Facebook page or similar social media are suitable, as the threshold for asking a question is quite low and the questions and answers remain available for other interested parties. It is recommended that any system used for answering questions should request some information from the questioners and should be moderated so that inappropriate comments can be removed while answers and appropriate comments remain accessible.

Rumours and misinformation proved hard to combat, as the company did not have a good platform for publishing responses to frequently asked questions. Another problem was an inability to determine when rumours started and, as a result, misinformation was widely spread. Talvivaara staff tried to correct misconceptions whenever they became known, but realises in retrospect that it should have also addressed the most common ones on the company's web pages to diffuse rumours with widely accessible factual information. It is hard to convince people that the company is not doing something that they had heard, from other sources for half a year that the company is doing.

Based on this experience, Talvivaara recommends a number of actions for public consultation programmes. Know your interest groups; if starting operations in a new region, engage representatives from the local population to help identify possible repercussions and fears. Establish and maintain an interactive form of communication, including a way for the public to receive answers to questions and, if possible, having the questions and answers available for any interested party (e.g. on a web page in the form of frequently asked questions). Have sufficient human resources on hand to answer questions from the public and to respond to interview requests. Establishing a dedicated team to oversee publicity and organise interviews is recommended, as is involving local community and businesses early in the process. Organise follow-up groups and/or open information meetings with the local population. Getting indications of approval from respected members of communities and local businesses will help immensely.

Do not expect people to know the facts about uranium or radiation (people can have fears for very unlikely things, such as deadly clouds of radon gas). Follow articles resulting from press releases and have background material available for reporters. Use of a national nuclear safety authority, if possible, or neutral third-party experts, will provide greater credibility. Be as open as possible when announcing results and keep interest groups well informed. It is better to provide too much information than to be accused of hiding facts.

There will always be vocal opponents against uranium mining. As long as the company can keep the conversation on facts, dealing with them is straightforward. But when the talk gets to fears and feelings, it becomes much harder to take part in the conversation.

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3.2. Environmental impact assessment (EIA)

An EIA is a process used to predict and minimise environmental effects of proposed initiatives before they are fully planned or undertaken. The EIA process is a planning and decision-making tool, as well as a public consultation tool that is used to inform and engage members of the public and other interested parties in a proposed activity in their region. Overall, the objectives of an environmental assessment are to incorporate environmental factors into decision making, identify potential environmental impacts of a proposed project and to outline ways of minimising or avoiding adverse environmental effects before a project is licensed and initiated. It provides all stakeholders with an overview of the project and details specific measures proposed to mitigate or minimise potential environmental impacts or effects that could arise if the project is to proceed. One challenge today is to ensure that there is only one EIA for a project and that all interested and appropriate regulatory parties from the region, state or national agencies participate in one joint EIA for the project with the public. It also provides for Aboriginal consultation on the project, where applicable.

The EIA process will determine if baseline environmental data collected for the region are sufficient, identify what key areas of the environment must be protected, adverse effects that must be avoided and what follow-up environmental monitoring programme must be put in place to assess the new project throughout its life cycle (i.e. during construction, operation, decommissioning and post-decommissioning). Some measures or goals to assess the effectiveness of the proposed controls or mitigation are also a recommended outcome of the EIA. This includes the identification of the regulatory controls or oversight that will be required to ensure that the project satisfies the overall recommendations from the EIA process.

A number of benefits arise from considering potential environmental effects and identifying mitigation measures early in the project planning process with an EIA, such as improving project decision making and public acceptance, as well as expediting regulatory and/or government approvals if the project is accepted. This includes the early identification of items such as:

- the adequacy of baseline environmental data prior to any development activity;
- whether significant design changes are needed to mitigate potential impacts;

- environmental resources that are at risk;
- project costs and potential project delays that could later arise.

Once completed, a properly conducted EIA will avoid or minimise adverse environmental effects, increase protection of human health and reduce the risks of long-term environmental impacts. The EIA process lays the groundwork for informed decisions that contribute to the responsible development of natural resources, including uranium.

In the United States, where several new ISL mining proposals were expected, a generic environmental impact statement (GEIS) was issued by the national nuclear regulator (NRC, 2009) that captured many similarities in ISL sites and grouped them into four specific geographic regions. When each separate licence application was received and reviewed, a supplement to the GEIS is completed to address more site-specific potential environmental impacts.

In the GEIS, common environmental issues associated with the construction, operation and decommissioning of ISL facilities, as well as groundwater restoration at such facilities are addressed, provided that they are located in the specified regions of the Western United States.

As noted in this report, the ISL method of extracting uranium has much less impact on the surface; however, protection of groundwater resources is particularly important. Since the hydrogeology of each site varies, these impacts require a greater amount of analysis and focus. In assessing potential groundwater impacts, possible contamination from operations and water withdrawal must both be assessed.

Public involvement is an important part of the environmental impact analysis process. In the development of the GEIS, multiple public scoping meetings were held in the geographic regions assessed and the public could comment on the draft documents. In particular native groups were identified and consulted in the process. These included, but are not limited to, the Navajo Nation, Hopi, Acoma Pueblo, Zuni Pueblo, Laguna Pueblo, and Great Sioux Nations. Outreach to native peoples is important to the United States and other countries and special opportunities for these groups to be involved in the project must be accommodated.

Case study: Moore Ranch Supplemental Environmental Assessment, United States

Preparatory licensing activities for the proposed Moore Ranch ISL project in the United States illustrate a comprehensive modern approach to environmental assessment. Informed by the regional GEIS, the nuclear regulator in the United States develops a supplemental EIS (SEIS) based principally on information submitted by the proponent. As a result, early in the permitting process a wide range of potential environmental impacts and the proponent's proposed approach to managing them are documented and discussed, allowing the regulator to develop project specific licensing recommendations. The SEIS covers a number of crucial features in any ISL operation, including baseline environmental data, confinement of groundwater in the mining zone, pressure testing of wells before operation, approaches to monitoring potential excursions, operating procedures to limit outflow of mining fluids from the mining zone, aquifer restoration approaches and goals, financial assurances and the consideration of the cumulative impacts of regional resource extraction projects.

Energy Metals Corporation submitted a licence application to the NRC of the United States for a new source material licence for the Moore Ranch ISL project on 2 October 2007. Based on this application and review of the supporting documents, NRC staff prepared an SEIS to evaluate the potential environmental impacts of the proposal to

construct, operate, conduct aquifer restoration and decommission an ISL facility. Unless otherwise indicated, this case study is based on the SEIS (NRC, 2010).

The Moore Ranch project is located in north-central Wyoming. The proposed licence area consists of approximately 2 880 ha of remote, privately owned land currently used principally for livestock grazing. It is situated within the Wyoming East Uranium Milling Region of the GEIS developed by the Nuclear Regulatory Commission (NRC). The GEIS provides a starting point for the NRC National Environmental Policy Act (NEPA) analysis for site-specific licence applications for new ISL facilities and applications to amend or renew existing licences. During the NRC's review of the application, Energy Metals Corporation U.S. was acquired by Uranium One Americas Inc. (Uranium One).

The comprehensive SEIS describes the environment potentially affected by the proposed site activities, presents the potential environmental impacts resulting from reasonable alternatives to the proposed action and describes Uranium One's environmental monitoring programme and proposed mitigation measures. It incorporates information and analyses by reference from the GEIS and uses information from the applicant's licence application and other sources to fulfil regulatory requirements and formulate the NRC staff recommendation regarding the proposed project.

Planned facilities include a central processing plant, two wellfields with injection, production and monitoring wells, header houses (sheds with equipment that controls injection and recovery wells), pipelines to connect the wellfields to the central plant and an access road network. Monitoring wells completed (i.e. finalised with casing and other components) in the production zone aquifer and in the overlying and underlying aquifers will be used to detect potential lixiviant (mining solution) movement out of the production zone.

During the preparation of the Moore Ranch SEIS, NRC staff met with federal, state, local agencies and authorities to gather additional site-specific information to assist in the review and to evaluate consistency between site and local data and information in the GEIS. NRC staff also contacted potentially interested Native American tribes and local authorities, entities and public interest groups in person, via email or telephone.

In addition to obtaining a source material licence from NRC, Uranium One is also required to obtain necessary permits and approvals from other federal, tribal and state agencies. These are required for *(i)* the underground injection of solutions and wastewater associated with the ISL process; *(ii)* the exemption of all or a portion of the extraction zone aquifer from regulation under the Safe Drinking Water Act; and *(iii)* the discharge of storm water during construction and operation of the facility.

As proposed, operations at the Moore Ranch Project would last about 12 years, although each wellfield would be operational for a little more than 3 years (Griffin, 2009). The central plant would operate at a maximum flow rate of approximately 11 364 L/min and is expected to produce 770 to 1 150 tU/yr. After uranium recovery has ended, the applicant would initiate aquifer restoration in each wellfield (NRC, 2008).

A comprehensive list of potential environmental impacts and health issues are addressed in the SEIS, based on the regional GEIS, the collection and analyses of existing environmental data from government agencies and companies that have worked in the area (including proponents who planned to mine the deposit by OPs in the 1970s), ecological samples, historic and cultural data collected in preparation for the licence application and a detailed characterisation of background radiological conditions prepared by the proponent (EMC, 2007a, 2007b). The applicant will be required to establish baseline water quality within specific wellfields and additional baseline radiological data as a licence condition. Throughout the life of the facility, the operator will be required to conduct an operational monitoring programme to measure and evaluate compliance with standards.

A relatively thick and low permeability aquitard (a geological stratum that retards water flow) separates the production aquifer from an underlying aquifer throughout much of the proposed licence area. Pumping tests indicate that the underlying aquifer is hydraulically isolated in Wellfield 1 and the potential for vertical excursions from the production zone into the underlying aquifer is small. In portions of Wellfield 2 however, the aquitard separating the production zone and underlying aquifer is missing and the two aquifers appear to be hydraulically interconnected. In this case, a deeper underlying aquifer, separated from the production zone by a continuous shale aquitard, would be treated as the underlying aquifer and well spacing adjusted accordingly, as required. The potential for vertical excursions from the production zone in Wellfield 2 into the underlying would be small.

The selected lixiviant must leach uranium from the host rock and keep it in solution during groundwater pumping from the host aquifer. The composition of the lixiviant is designed to reverse the geochemical conditions that led to uranium deposition. At Moore Ranch, the lixiviant would be alkaline, consisting of varying concentrations and combinations of sodium carbonate/bicarbonate and oxygen. It will be added to the native groundwater through injection wells to promote uranium dissolution. After transporting the pregnant (uranium laden) lixiviant to the surface through extraction wells and processing to extract the uranium, the barren lixiviant would be recharged with carbonate/bicarbonate and oxidant and re-injected into the ore body to continue extraction.

Experience shows that ISL wells must be constructed and installed correctly in order to avoid any excursions of the mining liquids. At Moore Ranch, all wells will be developed to remove any drilling fluids, restore the flow of formation water into the well and establish stable formation water chemistry in the well prior to being placed into service (EMC, 2007a; Uranium One, 2008). To ensure mechanical integrity of the wells, each will be tested for mechanical integrity before operation by pressure packing (i.e. sealing and over-pressuring the well to about 120% of maximum operating pressure and monitoring for any pressure loss). Any well that does not maintain at least 90% of the pressure for 10 minutes would be taken out of service and either repaired and retested or plugged and abandoned (EMC, 2007a; Uranium One, 2008). The purpose of this test is to verify that the well casing does not fail and result in fluid loss during injection or recovery operations.

Horizontal and vertical excursion monitoring wells would be installed in each wellfield, as dictated by geologic and hydrogeologic parameters. Wells to monitor potential horizontal excursions in the uranium recovery zone would be located in a ring around the wellfields. Wells to monitor potential vertical excursions would be placed in the first water-bearing sand above and below the extraction zone. These wells would be installed at a density of one well to every 1.6 ha of pattern area (Uranium One, 2009). Wells to monitor for horizontal excursions would be located in the extraction zone, approximately 152 m from the edge of the ore body and 152 m from one another around the wellfield perimeter. Proposed monitoring well locations may be adjusted as understanding of the ore body geometry is improved and for surface topography variations.

Monitoring wells will be sampled biweekly for chloride, alkalinity and conductivity (excursion parameters indicative of the presence of production fluids). Any well samples containing more than 2 of these excursion indicators at prescribed levels (derived based on background values) must be placed on excursion status and regulatory authorities notified within 24 hours. Wells on excursion status would be monitored every seven days until the indicators return to non-excursion levels. The applicant would modify wellfield operations, as necessary, to correct the excursion. If a well remains on excursion for more than 60 days, the applicant would provide a plan to the NRC to correct the excursion. If an excursion cannot be recovered, the licensee may be required to stop lixiviant injection.

All wells would be tested for mechanical integrity every five years to detect casing leaks and any well that failed these tests would either be corrected or removed from operation. The licensee would also follow an aggressive leak-detection and spill clean-up programme during operations. High- and low-flow alarms for individual wells would be the primary means for timely identification of a pipe rupture. Header houses would be equipped with a "wet building" alarm to detect the presence of liquids in building sumps. In addition, daily visual inspections of wellfields would occur.

Within each wellfield, more fluid will be withdrawn than injected to create an overall hydraulic cone of depression. Under this pressure gradient, groundwater movement would be from the surrounding area into the wellfield, minimising the potential for excursions outside the wellfield. NRC staff has documented historical information from operating ISL facilities where excursions have occurred and analysed the environmental impacts from both horizontal and vertical excursions in 60 events at 3 facilities (NRC, 2009). It was found that the licensees were able to control and reverse excursions through pumping and extraction at nearby wells for most events. Although most excursions were short-lived, a few continued for several years. In all cases, environmental impacts were small and temporary.

Aquifer restoration within the wellfield ensures that the water quality and groundwater use in surrounding aquifers would not be adversely affected by the uranium recovery operation (NRC, 2009). After uranium is recovered, the groundwater will contain constituents mobilised by the lixiviant. Groundwater quality in the exempted ore-bearing aquifer is required to be restored to *(i)* an NRC-approved baseline; *(ii)* a maximum contaminant level of specified constituents; or *(iii)* alternate concentration limits (ACLs) established by the NRC, if the baseline level of the constituents or the maximum concentration level values are not reasonably achievable. The development of ACLs is described in the SEIS. These standards are implemented during aquifer restoration to ensure public health and safety.

The applicant is required to provide financial sureties (assurance) to cover planned and delayed restoration costs that are reviewed annually by the NRC. Regulations require that applicants cover the costs to conduct decommissioning, reclamation of disturbed areas, waste disposal, dismantling, disposal of all facilities and groundwater restoration. The initial surety estimate would be based on the first year of operation. Annual revisions to the surety estimate are required to reflect existing operations and planned construction or operation the following year. Once regulators and Uranium One have agreed to the estimate, Uranium One would submit a reclamation performance bond, irrevocable letter of credit, or other approved surety instrument.

Under the Federal Underground Injection Control Programme, the exempted production aquifer will no longer be protected under the Safe Drinking Water Act as an underground source of drinking water. The exempted aquifer does not currently serve as a source of drinking water and cannot now and will not in the future serve as a source of drinking water.

The applicant will be required to establish baseline water quality for the site prior to the submission of a licence application. Prior to operations, the excursion parameters and upper concentration limits (UCLs) will be determined based on the baseline water quality sampled from additional monitoring wells placed in the ore-bearing, underlying and overlying aquifers. UCLs are used for control and management of excursions, should they occur during operations and restoration.

Aquifer restoration in each wellfield would begin as the uranium recovery operations end, shortening the period of groundwater contamination within the exempted aquifer. Evaluation of the degree of groundwater restoration within the production zone would be based on the average baseline quality over the production zone. The applicant would collect baseline water quality data for each wellfield from the wells completed in the planned production zone. Restoration would be evaluated on a parameter-by-parameter

basis, using "restoration target values" established for a list of baseline water quality parameters.

Uranium One would monitor the quality of groundwater in selected wells, as needed during restoration, to determine the efficiency of the operations and to decide if additional or alternate techniques would be necessary, as described in the SEIS. The evaluation of groundwater restoration within the production zone would be based on the average baseline quality over the production zone (EMC, 2007a). Online production wells used in restoration would be sampled for uranium concentration, conductivity and other constituents to determine restoration progress on a pattern by pattern basis.

During the groundwater treatment phase, water is pumped from the extraction zone to the surface for treatment. Three separate treatment technologies have been proposed for this step. Following treatment, groundwater would either be re-injected into the wellfield or disposed of via Class I deep disposal wells permitted by the Wyoming Department of Environmental Quality and reviewed by the NRC.

It is estimated by numerical modelling that the groundwater restoration phase would consume about 250 million to 350 million litres of water (EMC, 2007a). Upon completion of restoration activities, a minimum 12-month groundwater stability monitoring period would be implemented to demonstrate that the restoration goal has been adequately maintained.

Prior to decommissioning the central plant and associated structures, a preliminary radiological survey would be conducted to characterise the levels of contamination on structures and equipment, to identify any potential hazards and to support the development of procedures for dealing with such hazards prior to commencement of decommissioning activities.

Prior to release of the property for unrestricted use, the applicant would conduct a comprehensive radiation survey to establish that any contamination is within established limits. The applicant would return all lands to their previous use, unless an alternative was justified and approved by both the state and the landowner. The goal of decommissioning and reclamation is to return disturbed lands to production capacity equal to or better than conditions prior to uranium recovery. As part of this process, wells would be plugged and abandoned, disturbed lands would be reclaimed, contaminated equipment and materials would be removed, appropriate clean-up criteria for structures would be determined, items to be released for unrestricted use would be decontaminated and surveys would be performed to determine if there was residual contamination in soils and structures.

Wellfield plugging and surface reclamation would be initiated when the regulatory agencies concur that the groundwater in a wellfield has been adequately restored and that water quality is stable. Reclamation in the wellfield production unit would involve removing all surface and subsurface equipment, recontouring (if necessary) and conducting a final background gamma survey over the wellfield.

Some radioactive material would be released to the environment during Moore Ranch ISL operations The GEIS presented historical data for ISL operations, providing a range of estimated off-site doses associated with six current or former ISL facilities. For these operations, doses to potential off-site exposure (human receptor) locations range between 0.004 mSv/yr for the Crow Butte facility in Nebraska and 0.32 mSv/yr for the Irigaray facility in Wyoming, both well below the annual radiation dose limit of 1 mSv/yr (NRC, 2009). The maximum expected exposure to any member of the public from the proposed Moore Ranch Project is expected to be less than 0.1 mSv/yr at the site boundary (NRC, 2009). This exposure, combined with exposures from other facilities in the region is expected to remain far below the regulatory public limit of 1 mSv/yr and have a negligible contribution to the 6.2 mSv/yr average yearly dose received by a member of the public from all sources. Therefore, the proposed project is projected to have a small incremental

impact on public and occupational health and safety when added to the small cumulative impacts expected from other past, present and reasonably foreseeable future actions.

The GEIS also provides a summary of doses to occupationally exposed workers at other ISL facilities (NRC, 2009). Doses would be similar regardless of the facility's location and are well within the annual occupational dose limit in the United States of 50 mSv/yr. The largest annual average dose to a worker at a uranium recovery facility over a ten-year period (1994-2006) was 7 mSv. More recently, the maximum total dose equivalents reported for 2005 and 2006 were 6.75 mSv and 7.13 mSv. The primary source of exposure would be from the release of radon-222 during operations, including uranium extraction from the pregnant lixiviant, elution and subsequent precipitation of uranium, followed by the drying and packaging of the yellowcake for shipment.

The SEIS concludes that all impacts of the proposed project would be small (i.e. the environmental effects are not detectable or are so minor that they will neither destabilise nor noticeably alter any important attribute of the resource), with the exception of small to moderate (i.e. the environmental effects are sufficient to alter noticeably but not destabilise important attributes of the resource) socio-economic impacts during operation and cumulative impacts, owing respectively to limited housing available for workers and coal bed methane, other mining activities and oil and gas exploration in the region.

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3.3. Socio-economic impacts/benefits

The mining industry is a major force in the world economy, occupying a primary position at the start of the resource supply chain. The benefits of mining can be seen in a number of areas in many countries, including direct foreign investment, national investment, exports, net foreign exchange earnings, government revenues, gross domestic product, employment and wages (ICMM, 2012). These types of benefits can be significant drivers of national economies, particularly in the developing world.

As with all extractive industries, uranium mining has the potential to generate significant economic benefits. These can be seen directly through increased employment, training, salaries and wages and government revenues (royalties and taxes). It can also provide economic stimulus to the local and broader economy through secondary industries such as retail and service sectors that supply the mine and the mine's employees. Mining requirements for infrastructure such as roads, airports, electricity and water can lead to longer term regional development and this new infrastructure can remain after mine closure. Although these benefits can be significant, care must be taken to ensure that a just and proper portion of the benefits accrue locally. After all, it is at the local level that the impacts of mining will be greatest.

As outlined by the Canadian Manufacturers and Exporters (2012), uranium mining companies in Canada strive to fill all job vacancies with local residents and work with communities and various agencies to ensure that local residents are given priority access to pre-employment training programmes. The operators of the mine facilities (Cameco and AREVA) are signatories to the Multi-Party Training Plan, a training to employment initiative involving the provincial and federal governments, First Nations and Metis authorities. Over 3 000 employees and contractors were working at the mine facilities in 2012 and close to 50% were local residents of northern Saskatchewan. The companies are also committed to working with businesses in northern Saskatchewan to provide opportunities for northern procurement through the preferred suppliers programme. Of the over CAD 1 billion spent on goods and services by the mine operators in 2010, 75% went to Saskatchewan and 43% was spent in northern Saskatchewan.

In Australia, 4.25% of sales revenue from the Ranger mine is disbursed to Northern Territory Indigenous organisations and a further 1.25% of the royalty payments to the Commonwealth are disbursed to the government of the Northern Territory (ERA, n.d.). The mine operator, Energy Resources Australia, contributes to programmes identified by local communities, including over AUD 110 000 to partnerships and sponsorships in support of local schools and students, sports, the arts and regional festivals. The aim of the ERA Community Partnership Fund is to contribute to the development of a healthy and positive community by partnering with local businesses and communities to enhance educational and employment opportunities. The BHP Billiton Olympic Dam Corporation Pty Ltd (ODC) has undertaken a social monitoring programme to measure social effects from the current operations at the copper, uranium, gold and silver mine and to assess the performance of control measures put in place to minimise negative effects and maximise benefits (ODC, 2013). The programme focuses on community relations, employment, training and business benefits, housing supply and affordability as well as social character, amenity and well-being. An indenture agreement with the government of South Australia states that, as far as it is reasonable and economically practicable to do so, ODC will use available in South Australia services and labour and give consideration to South Australian companies when calling for tenders and letting contracts for site materials, plant equipment and supplies for the mine facility.

The Rössing Foundation, established in 1978 by Rössing Uranium Ltd, undertakes activities to assist local communities in achieving self-reliance through education, training, innovation and enterprise development in collaboration with the Namibian Ministry of Education and Ministry of Mines and Energy, the National Institute for Education, regional and local councils (Rössing Foundation, n.d.). The foundation has

built three modern mathematics and science centres and English language training centres, in addition to providing training, advice and facilitating loans to existing and emerging small and medium-sized enterprises in the region.

While uranium mining can make important contributors to the local economy, the mines are not permanent. Mine lifetimes vary considerably and although some can continue operating for decades, eventually either local resources will be depleted or the economics of the operation will change, leading to mine closure and decommissioning. Direct economic benefits from the activity will come to an end and the trained and experienced workers will have to seek employment elsewhere. In addition, during the operating lifetime of a mine, negative influences can take place, particularly at the local level, such as the disruption of traditional lifestyles, potential social pressures created by the influx of workers and, at times, increased wealth in small communities leading to dependencies and other social pressures. As a result, all socio-economic aspects of mining should be carefully evaluated prior to the development of a mine by the proponent, governments and the local community. Although uranium mining can provide important socio-economic benefits to local populations, the industry alone cannot be expected to resolve all regional socio-economic and development issues. Stakeholder consultation is critical in identifying issues of significance when focussing on the social component of the project (IAEA, 2010). This is typically undertaken during the EIA process.

In some cases, towns have been built to house employees and their families. For example, Roxby Downs (South Australia) was purpose built to service the Olympic Dam mine (www.roxbydowns.com). In Namibia, the town of Arandis was founded to house Rössing mine workers. In other cases, existing towns may expand due to an increase in the population because of mining activity. The development or upgrading of facilities such as schools and medical care centres, as well as policing to serve a larger population can also be funded through the economic benefits generated by a mine during operation. However, mine operations eventually close and if communities are totally reliant on the industry, they can depopulate rapidly and ultimately cease functioning as active communities, as occurred in Jeffrey City, Wyoming following the demise of the local uranium mining industry (Egan, n.d.).

There are also constraints on the speed of or the potential for economic growth from mining which stems from the limited capacity to provide these services and the necessary infrastructure. The need to protect the environment as well as cultural and historical heritage and the capacity of government to effectively regulate emerging mining industries, is a further constraint on growth.

An influx of workers to a region can put pressure on any existing infrastructure and on any existing community, including indigenous groups, as can be seen for example, with increased housing prices in mining regions. Further issues can be added to the mix in an existing settlement as a transient population with little or no ties to the region is introduced. In regions where workers are part of a fly-in-fly-out (FIFO) regime, where employees are flown in to the mining facility for a work shift (e.g. one week), then returned to their home residence for days off, these pressures can be eased.

The growth in the use of FIFO has prompted the Australian government to conduct an inquiry into the use of FIFO work practices in regional Australia. This inquiry will examine, among other things, the costs and benefits of an FIFO (and/or drive-in, drive-out) regime for companies and individuals, the effects on the communities and the potential opportunities for non-mining communities with narrow economic bases to diversify their economic base by providing an FIFO workforce. Once the inquiry has been concluded and the report released it will be made available through the Australian Parliament House website.

In regions where mines are more remote, such as in northern Saskatchewan (Canada), FIFO has been practised at uranium mines since the 1970s. It continues today, with pickup points at two of the major cities in the southern half of the province and multiple pickup points at small communities in northern Saskatchewan. The FIFO arrangement also allows trained employees to move to other sites as work requirements evolve, without having to move their residence and families.

In order to estimate the potential costs and benefits of uranium mining in a particular region, modelling of various site-specific scenarios should be undertaken. Although uranium mining is providing important socio-economic benefits to local populations, this point alone should not be taken as justification for proceeding with mine development.

Case study: Socio-economic impacts of uranium mining, Kazakhstan

Kazakhstan is a multi-ethnic country in Central Asia with a population of about 16 million. Development of the country's uranium resources in recent years has been dramatic. Fuelled by decades of local experience and expertise in ISL mining and significant foreign investment, annual uranium production has grown from about 3 700 tU in 2004 to over 20 000 tU in 2012. In 2009, Kazakhstan became the world's largest uranium producer and with its significant resource base and demonstrated ability to expand production it can be expected to continue as the world leader for some time. In addition to the industry generating significant economic development, employment and tax revenues, the government is making efforts to ensure that the industry contributes to socio-economic development of communities located in the vicinity of the mine facilities.

Since declaring independence from the Soviet Union in 1991, Kazakhstan has experienced a remarkable economic transformation (Knox, 2011), modernising and undergoing deep socio-economic change. Between 2000 and 2009, the economy of the Republic of Kazakhstan grew at a rate of between eight and nine per cent, making it one of the ten fastest growing countries in the world. Per capita income has doubled and the unemployment rate has been halved (OECD, 2011). While general wealth has increased and poverty has declined, economic inequality continues to be a major challenge.

The main driver of the economy is the development, extraction and export of Kazakhstan's significant endowment of oil, gas, minerals and metals, including uranium. Like many countries that produced uranium in the Cold War for military purposes and in the 1970s when rapid expansion of civilian nuclear power was envisioned, the industry went into decline when both military and civilian demand waned in the 1980s. As the industry declined so too did the communities that developed around the production facilities and were economically dependent on mining. This was particularly pronounced in several central Asian countries after the dissolution of the Soviet Union in 1991.

Following independence, ownership of all nuclear facilities in Kazakhstan became the property of the government. In 1997, the government-owned National Atomic Company Kazatomprom JSC was formed to focus on the exploration, mining and processing of uranium and rare earth minerals, along with other civilian nuclear activities. As mine development proceeded, the Kazatomprom-Demeu subsidiary was established in 2004 to improve social conditions and raise the standard of living in the uranium mining regions of the country (Kazatomprom-Demeu, n.d.).

In order to provide funding for Kazatomprom-Demeu activities, all contracts for uranium exploration and mining with the government of Kazakhstan require the payment of financial contributions for local social and cultural improvements. The funding finances the establishment, development, maintenance and support of the regional social sphere, including health care, educational and sporting facilities for employees and local citizens, training for small business development and infrastructure

maintenance and improvement in local communities, in accordance with the strategy of Kazatomprom and agreements with local authorities. Annual contributions from each operator amount to between USD 30 000 and USD 100 000 during the exploration period and up to 15% of annual operational expenses (or USD 50 000 to USD 350 000) during the operation of a mining facility (NEA/IAEA, 2012).

As outlined by Kazatomprom-Demeu (n.d.), the company has been engaged in financing, purchasing equipment and implementing construction work and capital repairs of schools, kindergartens, hospitals, clubs and other social facilities in southern Kazakhstan where about 90% of national uranium production takes place. Funding amounts are increasing annually as the industry grows. As a result, uranium mine development is not only contributing to national economic development but also to local development and prosperity in outlying regions of the country.

The establishment of medical service centres was an early priority for Kazatomprom-Demeu in order to provide modern treatment facilities and services to Kazatomprom employees and local inhabitants. Medical examinations and lectures on preventative practices are provided to community members and in schools. To improve education standards, schools with modern equipment and supplies have been established, providing a continuous programme of education from an early age through secondary school. As early as 2008, entrance rates to post-secondary centres of education have improved for students graduating from schools in the uranium mining region. Salary increases and bonuses for teachers in specific subject areas have improved service delivery standards and a sponsorship programme for disadvantaged children, providing school supplies, clothing and meals, has expanded access. An annual English language Olympiad has been instituted to promote acquisition of the language and students with demonstrated ability in the competition have been rewarded with trips to Great Britain to accelerate development of language skills.

To promote cultural development and a healthy lifestyle, cultural and sport centres with libraries, child entertainment areas, gyms, training equipment, computers and cinemas have been built in 3 settlements, leading to the establishment of over 50 hobby and sports clubs involving over 2 500 children. Annual regional sport competitions for young and old are held, along with cultural events on national holidays. Activities are directed by qualified staff. Kazatomprom-Demeu initiatives also include assistance in the development of local businesses, recognising that the uranium industry alone cannot provide employment for all local inhabitants. Trained specialists assist local entrepreneurs, with priority given to projects capable of creating additional employment opportunities for locals, in particular in the areas of livestock production and processing. Moreover, the company also carries out infrastructure maintenance in local communities, including road work, landscaping, removal of wastes and water treatment facilities.

In 2010, about 9 000 were employed at the operating uranium production centres in Kazakhstan (NEA/IAEA, 2012). According to the subsoil use contracts with the state, obligatory training taxes amounting to about 1% of annual exploration expenses and 1% of annual expenses during uranium production are collected. Owing to the rapid expansion of uranium production, shortages of qualified staff became an issue in 2009 and 2010. To build capacity and address this issue, training was conducted in two educational centres, drawing on local residents near the existing production centres in the Kyzylorda (Shieli) and southern Kazakhstan (Taukent) regions. The Kazakhstan Nuclear University, founded by Kazatomprom, along with the Regional Geotechnology Training Center were involved in training to raise the skill levels of new personnel. New uranium production centres also create opportunities for students in higher and secondary technical institutes in Kazakhstan.

While the uranium industry alone cannot solve all the inequality issues facing the country, the government is working to ensure that the industry is contributing to improving the regional standard of living, services and infrastructure, as well as

providing development opportunities to local inhabitants, the population most affected by the mining developments. Given the size of the existing uranium resource base and the potential for new discoveries, uranium mining can be expected to contribute to local economic development for decades to come.

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3.4. Environmental monitoring

In its early history, all types of mining and milling facilities throughout the world often had little or no environmental monitoring and the result was often widespread contamination that required challenging and costly remediation efforts. Had the consequences been better understood and sufficient environmental monitoring programmes been in place when mining began, contamination could have been detected early and addressed. With heightened awareness and development of regulatory oversight in the 1970s, a significantly increased effort has been placed on establishing adequate environmental monitoring programmes.

Monitoring provides the data that allows comparison of facility performance against targets and requirements set out within the EIA and licence conditions of the operation. The general purpose of monitoring is to check whether operations are impacting the environment beyond limits established by the regulator and whether rehabilitation works are performing as predicted.

Environmental monitoring is an essential safety and environmental protection function of any uranium mining facility and the collection of sufficient baseline data is essential in order to design and carry out a proper environmental monitoring programme. It is only when compared with the pre-mining (baseline) conditions that the impact of the operation can be objectively assessed. This reinforces the need to begin collecting baseline information early in the exploration phase, before the site undergoes any significant physical disturbance. Typically, pre-operational monitoring of air, water, soil, sediment, vegetation, biota and biodiversity, direct radiation and radon flux sampling should be in place for at least twelve consecutive months, as appropriate to the site and local circumstances.

Installation of a meteorological station to collect pertinent information such as prevailing wind direction is often required to properly situate environmental atmospheric and dust monitoring stations. The collection of accurate wind pattern data is essential to guide correct placement of environmental monitoring stations in order to assess potential excursions from predicted impacts.

There are two types of monitoring programmes typically conducted to measure performance against baseline data (IAEA, 2010). Impact or compliance monitoring is designed to check on a regular basis whether the facility is having an impact on the receiving environment during operations and to ensure that commitments and statutory obligations are being complied with. A compliance monitoring programme usually consists of the pre-monitoring elements listed above. A correctly designed impact/compliance monitoring programme will be able to provide early warning of adverse environmental impacts.

Performance monitoring is developed to assess whether remediated sites are meeting predicted outcomes required by relevant regulatory agencies to help to ensure that closure criteria are being and will continue to be met. An additional outcome of performance monitoring is to provide field measurements that can be used to refine and calibrate models used in the design of remediation works, in particular groundwater protection and tailings cover designs. Monitoring data can also be used as input to adaptive management techniques; an iterative process of assessing issues and adapting responses to them through a cycle of identification, design, implementation and monitoring until the desired objectives are met. This cycle continues until the uncertainty associated with any new policy, practice or system has been minimised and performance has been optimised.

Monitoring data is of little value if it is not regularly reviewed. Historically, operations have collected large amounts of costly monitoring data but then failed to interpret the information adequately. Operators need to be aware of the potential impacts of a change in an operation's scope over time and the potential implications of any change to the monitoring programme As a result, monitoring programmes should be reviewed regularly to ensure that they remain relevant in terms of the parameters being monitored, the location of monitoring stations and the frequency with which monitoring is being conducted. Reports must be submitted to regulators and preferably made available to the public, typically on a semi-annual or annual basis.

Water quality monitoring upstream and downstream of the site must include all adjacent streams, rivers, lakes and intermittent streams. Typically it must be performed seasonally during dry periods, winter conditions, spring runoff, or during the rainy season in tropical climates. A periodic full sweep of parameters is typically required, interspersed with more routine reviews focused on a smaller number of parameters of concern. This can be an effective, efficient and cost effective method for some of the key aspects being monitored.

Examples of recent regulatory guidance on monitoring programmes in general and radon emission in particular are provided by the Canadian Nuclear Safety Commission (CNSC, 2003, 2006). The United States has also issued a regulatory document on

managing radiological effluent and environmental monitoring (NRC, 1980) that may provide useful guidance to developing countries, although it is under revision and will be issued for public comment before being finalised. As always, the local climate, physical and social circumstances should be considered on a project to project basis. Although such guidance is helpful, it is important to recognise that the regulatory framework and requirements can vary from country to country.

Case study: Athabasca Working Group, Canada

Canadian uranium mines are required to report regularly on extensive, site-specific environmental effects monitoring programmes included in licence conditions approved by federal and provincial regulators. In addition to these site-specific monitoring requirements, the companies operating in northern Saskatchewan have instituted a community-based environmental monitoring programme to provide assurance to local residents that the operations are not impacting the regional environment. This programme allows local residents to assist in the determination of sampling points, the collection of samples and the interpretation of the monitoring data. In addition, the provincial government has established and continues to support Environmental Quality Committees staffed by local residents to improve communication between the industry, government and local residents. These types of programmes increase understanding of uranium mining activities and help establish trust in local residents that the environmental impacts of uranium mining do not pose a health or environmental risk, a key to maintaining a social licence to mine.

As outlined by the national nuclear regulator, the Canadian Nuclear Safety Commission (CNSC, 2010), extensive environmental effects monitoring programmes have been implemented at uranium mining, milling and processing facilities to identify the impacts on the receiving environment of contaminants of potential concern and to ensure that licensees are taking all reasonable precautions to control releases. Effluent and environmental monitoring programmes are developed on a risk basis and depend upon the complexity of the released effluents, the sensitivity of the receiving environment and the anticipated effects on the environment. In 2010, the uranium mining sector of the metal mining industry was the best performing mining sector relative to the metal mining effluent limits, with no discharges in excess of regulatory limits.

Moreover, the CNSC (2012) notes that results of environmental monitoring in northern Saskatchewan show that the uranium mines have no effect on radon levels and that uranium, radium-226, lead-210 and polonium-210 levels in fish are often below detection thresholds. Even when measurable the levels of these contaminants are no different around the mine sites than levels measured in nearby or remote reference sites. In addition, uranium releases from mines and mills area at levels well below those that could pose a health hazard.

Beyond meeting regulatory requirements, the operators of the uranium mines in Canada have instituted and provide support for a community-based monitoring programme. The Athabasca Working Group (AWG), created in 1993 by representatives from local communities and uranium mining company representatives (AWG, 2012), involving six of the seven Athabasca communities and the two mining companies (Cameco Corporation and AREVA Resources Canada Inc.), undertakes this work along with other activities. Further discussions led to the development and implementation of the Impact Management Agreement (IMA) in 2001 that covers, among other items, environmental protection.

The community-based environmental monitoring programme of the AWG continued through 2011 for the eleventh consecutive year. The mining companies provide funding

to train community members in the collection of environmental samples (including air, water, fish, animals and lake sediments) which are then independently analysed at laboratories in Saskatchewan and the United States (Cameco, n.d.). Expenses for the monitoring programme for 2011 amounted to about CAD 250 000. Local communities are responsible for appointing representatives to participate in the monitoring as well as selecting local people who, during the course of normal hunting/trapping activities, obtain moose, caribou and lynx samples for the programme. The first samples were collected in June and September 2000 and the programme continued through 2011 using the same months for sample collection. The data collected in this programme show that contaminants of concern are well below established regulatory standard government guidelines, no areas of environmental concern have been identified and no measureable impact on the environment from uranium exploration or mining has been documented.

One section of the IMA outlines the action to be taken in case of a loss caused by mine emissions or spills and the types of losses covered as well as the claim settlement process and types of compensation available. The local monitoring programme, assisted by local residents, is part of the process to determine if a loss has occurred. The community-based environmental monitoring programme became part of the IMA following several years of discussion among AWG members. There is a strong emphasis on community involvement and AWG members provide feedback to help identify specific monitoring stations near each community.

In addition to industry initiatives, the provincial government has established the Northern Mines Monitoring Secretariat (NMMS), an inter-ministerial committee chaired by Saskatchewan Northern Affairs that is dedicated to informing northerners about the uranium mining industry. The NMMS include members from the Canadian Nuclear Safety Commission and provincial ministries that regulate and/or support the uranium industry.

The NMMS provides technical and organisational support to the Environmental Quality Committee (EQC), an organisation composed of people nominated by their community to act as bridge between the communities, government and the uranium mining industry. There are currently 3 EQC subcommittees (Western, South Central and Eastern) representing 32 municipal and First Nation communities. The EQC meets on average four times per year, inviting the regulators, provincial government and uranium mine licensees to participate and provide technical presentations. The EQC also tours the active uranium mine sites on a yearly basis.

The EQC enables area residents to learn more about uranium mining activities by seeing the environmental protection measures being employed and the socio-economic benefits stemming from the industry. The EQC has no decision-making responsibilities and is structured to provide a forum to ensure the concerns and recommendations of northerners regarding uranium development in northern Saskatchewan are heard and considered. The EQC has become a participant in uranium mine and mill licence renewals, providing input into the decisions of Canadian regulators.

Initiatives such as these not only add to the data collected in environmental monitoring programmes required by regulators, they assist in building public confidence by allowing members of the public to plan and participate in sample collection and to interpret the results.

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3.5. Financial assurance

Mining is a temporary use of the land. Eventually, mineral resources become depleted and the productive life of a mine comes to an end. Mine sites then enter the period of reclamation and remediation to rehabilitate areas disturbed by mining activities in order to leave them in a safe and stable state. Criteria for any type of mine closure are developed according to the intended post-closure land use to protect human and environmental health. If funding is not put aside for site reclamation early in the mine life, the mine operator could fall short of funding to implement a reclamation programme that meets the expectations of stakeholders, including regulatory agencies.

In the early era of uranium production, mining in many jurisdictions was conducted by national or pseudo-national institutions, driven by uranium requirements arising from Cold War nuclear arms race. The extraction of uranium in this early era was considered a matter of national security. Little importance was given to the management of mine wastes and environmental legacies resulted in uranium mining jurisdictions such as Australia, Canada, Germany, the Russian Federation and the United States. Consequently, the reclamation and rehabilitation of these historic uranium mine sites has required substantial governmental funding to achieve safe and stable states.

Financial assurances are instruments established to guarantee that funds required to achieve rehabilitation and mine closure are in place, irrespective of the status of the mine operator. Government policies that require financial assurances are broadly established in mining jurisdictions around the world. In Canada, for example, the first legislation to require financial assurances for uranium mines was enacted in 1994 by the then Atomic Energy Control Board (now the Canadian Nuclear Safety Commission). There are many different varieties of financial instruments developed to provide governments with financial assurance, including cash deposits, trust funds, letters of credit, insurance policies and bonds.

To determine the value of the financial assurance required, mine reclamation and potential long-term care costs must be forecast. In many mining jurisdictions requirements have evolved to call for the development of mine reclamation plans at the time of initial permitting, with forecasted costs of future remedial work and corresponding financial assurances provided. As mine activities develop, re-forecasting is periodically required (e.g. every one to five years). To account for limitations encountered when forecasting costs of activities far into the future, including reasonably foreseeable uncertainties, the value of financial assurances can be substantial. Future rehabilitation costs, as well as the cost of financial assurances which must be maintained to address them, are effective motivators to minimise environmental liabilities during the operating period.

Requirements to develop and fund closure plans are integrated into the principles of leading international industry and governmental organisations which oversee both mining and the nuclear industry:

- The ICMM (2008) directs proponents to "design and plan all operations so that adequate resources are available to meet the closure requirements of all operations" as an objective under ICMM principle 6: "seek continual improvement of our environmental performance".
- The International Finance Corporation of the World Bank Group establishes environmental performance standards to be achieved throughout a project life cycle and provides loan guidance to Equator Principles financial institutions to include covenants regarding the establishment and funding of decommissioning plans (Equator Principles, 2009, 2013).
- The IAEA (2006) establishes within its *Fundamental Safety Principles* that "people and the environment, present and future, must be protected against radiation risks" and requires signatories to the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* (IAEA, 1997) that contracting parties ensure adequate financial resources are available for decommissioning.
- The World Nuclear Association (WNA, 2006) expands the ICMM principles and objectives within its *Sustaining Global Best Practices in Uranium Mining and Processing* with the commitment on behalf of uranium mining industry to "engage in no activities or acts of omission that could result in the abandonment of a site without plans and resources for full and effective decommissioning or that would pose a burden or threat to future generations".

Planning for mine closure has become an integral part of mine life cycle planning. Documenting rehabilitation plans for decommissioning mine sites and ensuring that financial resources are in place to manage mine closure has evolved from best practice to common practice in leading practice jurisdictions. International agencies and associations which govern mining and the nuclear industry have integrated into their policies, principles and guidance measures to ensure that the uranium mining industry does not generate liabilities which burden future generations. Correspondingly, over the past 30 years, requirements by national agencies in mining jurisdictions have been increasingly codified into regulatory instruments that demand formalised decommissioning plans and financial assurances to protect human and environmental health and public coffers.

Financial assurance amounts vary with clean-up costs calculated according to the type of and extent of mining undertaken to reflect the full third-party costs of site clean-up. For example, financial assurances for the Cluff Lake uranium mine and mill in Canada amounted to CAD 33.8 million during operations, owing to the complexity of the decommissioning and remediation of a facility that included OP and UG mines, a tailings management area, waste rock disposal areas, a mill and associated facilities (Pollock and

Hillier, 2011). In contrast, given the limited land disturbance and the absence of mill tailings and waste rock in ISL developments, the amount of financial assurance required is generally reduced compared to OP and UG operations, for example less than USD 7 million for ISL operations in the United States (Markey, 2012). Periodic review and adjustment of the financial guarantee for a particular site would include reductions associated with approved decommissioning of facility components accomplished during the operational phase (where possible) that reduce overall decommissioning costs. This has the added benefit of encouraging producers to conduct remediation activities during operations.

Case study: Saskatchewan Institutional Control Program, Canada

Financial assurance is a requirement in countries with leading practice uranium mines for all phases of the life cycle of a mine. However, in order for uranium mining companies to understand operational and financial requirements in the long term, a clear understanding of requirements that must be met in order for properly decommissioned mining properties to be returned to the land owner, typically the government, must be established. The institutional control framework in Saskatchewan is an example of the process and conditions required to return leased industrial land to the land owner, in this case the province, following decommissioning and a monitoring period to confirm that closure targets have been achieved. To ensure that any necessary work at a decommissioned site is carried on well into the future, financial assurance is required for regular monitoring and maintenance, as well as for unforeseen events, such as damages resulting from severe natural events.

In 2005, the government of Saskatchewan initiated formal development of the institutional control framework for the long-term management of decommissioned mine and mill sites on provincial Crown land. The framework was developed to ensure the health, safety and well-being of future generations and to provide greater certainty for the mining industry. Such a programme for uranium mining facilities not only protects future generations, it also provides greater certainty with respect to the end point in mining operations in a way that meets national and international obligations for the storage of radioactive materials (Pollock and Hiller, 2011).

An interdepartmental working group of senior departmental representatives undertook development of the framework and consultations were held with stakeholders, including federal regulators, industry, aboriginals and northerners, special interest groups and the general public. In May 2006, the provincial legislature promulgated The Reclaimed Industrial Sites Act (Saskatchewan, 2009) to implement and enforce the recognised need for institutional controls. With the act in place, the working group proceeded with the development of The Reclaimed Industrial Sites Regulations, which were subsequently approved in March 2007. The act and regulations govern the establishment of the Institutional Control Program (ICP). In the case of a uranium site, the ICP explicitly recognises the jurisdictional authority of the federal Nuclear Safety and Control Act as enforced by the national nuclear regulator, the CNSC.

The two primary components of Saskatchewan's ICP are a registry and two types of funding for monitoring and maintenance and for unforeseen events. The purpose of the registry is to maintain a formal record of the closed sites, manage the funding and to perform any required monitoring and maintenance work. The monitoring and maintenance fund will pay for these long-term activities, while the unforeseen events fund will pay for damages resulting from severe natural events, such as floods or tornadoes.

The funds are managed by the province, but are legislated and independent from provincial revenue. A mining site will be accepted into the ICP after remediation activities

have taken place, regulatory authorities have issued a release and the site holder has completed and complied with the conditions of any environmental assessment requirements. In addition, a monitoring and maintenance plan must be submitted that identifies tasks that need to be undertaken when the closed site is accepted into the ICP, along with a determination of the present value of all future costs associated with monitoring and maintenance. In return, the site holder surrenders or transfers the mineral rights to the provincial government.

For the government to accept a closed site into the ICP, the site holder must post financial assurance in an amount equal to the cost of a maximum failure event identified in the monitoring and maintenance plan that could occur at the closed site or an otherwise agreed basis.

After the operator has completed the approved decommissioning and reclamation activities, the site enters a period of "transition phase monitoring". During the transition phase monitoring period, the operator is required to continue monitoring and maintaining the site, as per the requirements in the plan, at their own expense. The operator is also required to maintain sufficient financial assurance to cover the cost of the remaining obligations outlined in the plan and any monitoring and maintenance requirements for the balance of the transitional period as well as a negotiated contingency for any unexpected occurrences. During the transition phase monitoring period, regulators continue to conduct periodic inspections and review monitoring results and the operator continues to remain fully liable for any impacts the site may have on the environment, surrounding communities and public safety (Saskatchewan, 2006).

If the site performs in accordance with the decommissioning and reclamation plan and achieves the predicted stability during transition phase monitoring, the operator may make an application to obtain a release from further monitoring and maintenance responsibilities and the obligation to maintain financial assurance. At this time the operator may then proceed to apply for a release from its surface lease, allowing the transfer of custodial responsibility for the property from the operator to the ICP registry.

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3.6. Product transport

During uranium mining operations, transportation of various hazardous materials is required. These comprise of a variety of operating materials, such as acid, alkali, fuels and explosives, as well as low-level radioactive waste rock and the final or interim product (e.g. UOC or uranium-containing resin). Here the focus is on the transport of UOC, which is of increased interest due to expectations that increasing uranium demand will drive expansions and development of new mining operations in various jurisdictions. The imbalance between uranium producing and consuming countries, as well as the limited number of conversion facilities, makes long and safe transportation a necessity.

Usually dangerous goods are transported by road, rail and/or sea. These movements are regulated by the competent authorities in the respective countries, depending on the mode of transportation. Requirements for safe shipments of hazardous materials are also reflected in international agreements, for example Recommendations on the Transport of Dangerous Goods (UN, 2013) and the International Maritime Dangerous Goods Code (IMO, 2012).

Regulations governing the transport of radioactive material were first introduced in 1961, have been updated regularly and subsequently adopted in the abovementioned agreements and regulations (IAEA, 2009, 2012). The IAEA regulations contain a classification scheme for radioactive materials as well as testing procedures and requirements for transportation and packaging, with a focus on the provision of adequate packaging to safely contain the radioactive material during normal handling and accident conditions. Additional requirements for packaging and transport are defined according to the activity and the state of the material. Due to its low activity per unit mass, UOC is considered a low hazard and can therefore be transported as an industrial package with appropriate placarding and labels.

The shipment of UOC is currently carried out in sealed, reusable steel drums, which are loaded in ISO containers. To ensure safe and efficient transport, good industry practices have been defined and implemented, including recommendations for drum design, size, materials and labelling, as well as requirements for lids and rings. Additional focus is given to loading the drums into the containers and adequately securing the drums. Furthermore external, non-fixed radiation (e.g. attached dust) is to be kept low to avoid cross contamination and a programme on-site is required to verify that the drums are clean (i.e. there is no contamination on the outside of the drum). This is of special importance because the containers are generally multi-use, since returning them to the producer empty would be too costly in many cases. Therefore, if containers are released for general transport, it has to be confirmed that there is no activity above specified limits (i.e. 4 Bq/cm² for non-fixed beta, gamma and low toxicity alpha emitters, such as UOC; IAEA, 2012). Every instance of contamination or damage to drums discovered has to be reported according to regulatory requirements. Although UOC consists mainly of uranium, its radioactivity per mass is well below the activity of the ore. This is because other radioactive elements of the uranium decay chain remain with the tailings in the milling process. However, since gamma exposure rates increase with time, they only become a more important consideration if transportation spans several weeks. Therefore the main health concern from UOC is due to its chemical toxicity as a heavy metal, rather than its radioactivity. If adequately packed and handled no health hazard is expected

from the uranium concentrates and annual individual doses should not exceed 1 mSv. As for every radioactive material, the regulatory requirement for minimising does and releases of radioactive material applies to keep exposures as low as reasonably achievable, societal and economic factors taken into account.

Figure 3.1. UOC shipping drum



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Producers and transporters have to be aware that they are dealing with a sensitive cargo when handling radioactive material, since radioactivity is typically a topic of public concern. Therefore a comprehensive emergency plan has to be developed in the case of a spill and/or accident. This includes active risk communication to the public, first response training for drivers to initially minimise the impacts and the provision of qualified response units along the transportation route. A framework for planning and preparing for accident response has been developed by the IAEA (2002).

Over recent years greater attention has been devoted to security aspects of UOC transport. Although it can be challenging, providing physical protection and following the regulations regarding the proper transport of radioactive substances is more important today in order to avoid illegal acquisition and illicit trafficking (IAEA, 2008).

Early in the development of nuclear energy it was recognised that the transport of UOC posed a potential environmental and security risk. Therefore strict regimes, as outlined above, were instituted as early as the 1960s. In the late 1990s the World Nuclear Transport Institute (WNTI) was founded by industry to represent the collective interests of the radioactive materials transport sector (WNTI, 2010a, 2010b, 2010c). As a result, the transportation of nuclear material sector has a very good safety record, which is especially imposing due to the great distances involved and the large number of shipments. Although the concentrates are transported from around the world to the few existing conversion and enrichment facilities, no accident in transport of UOC resulting in serious harm to people or the environment has been recorded. Furthermore, the hazardous potential of the ore concentrates is rather low. Nonetheless, an accident involving UOC cannot be precluded and the implementation of accident management plans and exchange of experiences in handling such incidents is required.

A recent French report (IRSN, 2013) identified 44 fuel cycle "anomalous" transportation events between 1999 and 2011 arising from an annual average of 900 000 radioactive material shipments in France. Missing transport documents, errors in

these documents or in package or vehicle labelling and surface contamination of shipping vehicles and/or containers were the primary reasons for the reported events. Although these events do not generally jeopardise transport safety, oversights like these could have consequences in accidents of a more serious nature if information on the contents or the containers themselves is inaccurate and/or missing. None of the surface contamination events led to exposure or contamination of the operators involved and their impact on the environment is negligible.

IAEA Regulations for the Safe Transport of Radioactive Material (IAEA, 2012) have become an internationally accepted standard for governments and the industry. It is incumbent upon every state to adopt these regulations and they have been adopted in about 60 countries. To avoid delays or denials of shipment at the interface of different regulatory regimes, having a broad acceptance of these regulations is important since the transport of UOC involves large distances and many countries. Following these practices is necessary to prevent authorities or carriers from refusing shipments. In addition, information campaigns by the Australian government, the IAEA and the WNTI are required to ensure that port authorities understand the risks and hazards associated with maritime shipments of UOC.

Case study: Emergency preparedness in uranium transport, Canada

The global transportation of nuclear material over the past several decades has a very good safety record. Nonetheless, an accident involving UOC cannot be precluded and the implementation of accident management plans is required. This case study outlines emergency preparedness and response planning by Canada's uranium producers as an example of leading practices, showing that the training undertaken, advance contact with local authorities and the careful choice of transport contractors helps prepare for an appropriate response in the case of an accident.

The basic prerequisite for safe transport of UOC is compliance with national regulations. The Canadian Packaging and Transport of Nuclear Substances Regulations that define requirements for labelling, transportation and packaging of nuclear materials were largely adopted from IAEA transportation regulations.

Emergency response at mining companies

Producers are fully aware that they are dealing with a sensitive issue when handling UOC. Not only is it classified as a hazardous material; it is a commodity of concern for the public and first responders. As a result, high priority is given to the safe transport of radioactive products, as indicated by need for an Emergency Response Assistance Plan (ERAP) in Canada that defines the organisational structure of the emergency response, duties and responsibilities (including flow charts for notifications and actions), emergency levels, internal and external resources and post incident actions (TC, n.d.). The ERAP identifies the following key points for emergency response in the case of an accident compromising the packaging of the uranium products, including:

- provision of first responders to the incident scene;
- provision of radiation protection specialist(s);
- access control at the incident scene;
- containment of any released materials and mitigation of risks;
- clean-up of the affected areas and disposal of the contaminated materials;
- verification of adequate clean-up and decontamination;
- management of field operations and external communications;

- support of emergency operations;
- provision of first aid and transportation.

The highest organisational level in case of an incident is the Emergency Operations Centre. It is responsible for making key decisions, contacting governmental bodies, the public and other organisations, as well as tracking events and the effectiveness of the emergency response.

The situation on-site is first assessed by an Initial Response Team (IRT). The team develops and directs the implementation of strategies for achieving emergency response objectives in contact with regional authorities. The IRT establishes objectives and priorities, manages emergency response resources and ensures that the ERAP is properly implemented while keeping contact with the Emergency Operations Centre.

If necessary, a Full Clean-up Team can be deployed, consisting of the IRT plus additional emergency response personnel and/or response teams from contracted emergency response service providers. The Full Clean-up Team works at the scene performing necessary clean-up actions, such as the recovery of nuclear material, monitoring and controlling access. It must be noted however, that the authority at a transportation incident on public property rests with the local police or fire department. The company's response team serves as technical advisors in support of these local authorities.

For all personnel involved in emergency response, company staff as well as external service providers, training and refresher courses are of great importance and thus carried out regularly. The training comprises ERAP familiarisation, illustration of hazards associated with UOC and uranium ore slurry and specific guidance for first responders and the full clean-up team. It is also crucial to have equipment serviced and ready to use so it can be deployed on short notice.

Transportation companies

Equally important as the emergency response by the company and the service providers is the careful selection of trucking companies, which have to be aware of issues when transporting radioactive substances. Therefore safety, health, environmental and quality audits with trucking companies and freight forwarders are conducted by Canadian mining companies. This ensures compliance with health and safety regulations and adherence to the principles of good environmental and quality control practices. Specific training for drivers as well as the definition of actions for the driver is helpful in mitigating effects in the initial phase of an accident.

Full-scale transport incident exercises are arranged, involving stakeholders such as transport companies, freight forwarders, regulators, contracted transportation emergency responders and first responders. These exercises help to improve the skills of local responders and drivers in transport companies hauling the product.

First Responder Outreach Programme

In case of an accident, firefighters, police and an ambulance would typically arrive at the site first. These first responders must have a basic understanding of the properties and hazards of the uranium products in order to respond appropriately.

About ten years ago, mining companies started to provide awareness training to first responders along transportation routes. It turned out that few of the first responders realised that UOC was being moved through their communities. They therefore welcomed information on what UOC looks like, what hazards and radiation can be expected and the most appropriate methods of protecting themselves and the environment at an accident scene. This also enables relief units to put radioactive material in perspective with other hazardous material that they are more accustomed to

dealing with. In recent years, training awareness and understanding on UOC and its actual risks has been expanded to port authorities, fire departments and contractors along Canadian transportation routes. In highly populated areas, where it is not possible to reach every community, subordinate emergency management authorities that would be contacted in the event of an accident involving any hazardous material were visited and informed.

A second benefit arising from the awareness training is contact with emergency responders is established, thereby avoiding the situation where the first meeting between the companies' IRT and the authorities occurs at a (possibly stressful) accident site.

This example illustrates the essential points of a comprehensive emergency preparedness. Although a good internal training and preparation is required, training of transportation company personnel and service providers is essential. It is important that the authorities and first responders are informed about the properties, hazards and proper handling of the material, since they are vested with decision-making powers at the accident scene. Furthermore, open information policies will always improve relations with and acceptance by the public.

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3.7. Emergency planning

Emergency planning encompasses both emergency preparedness and emergency response activities. At any mining site emergency planning is part of the daily business, as hazardous operating materials are regularly used, such as aggressive chemicals and explosives. Beyond this, radiological hazards have to be considered for uranium mining

and milling. As these facilities deal with low-level radioactive material, the major preparedness and preparation measures for on-site emergencies are covered within the radiation protection programme.

Emergency preparedness is related to the type of mining undertaken, as different emergency scenarios have to be considered for UG, OP or ISL mining. In general, no off-site consequences, radiological or otherwise, are expected from uranium mining operations. However, off-site contamination requiring intervention could occur for example, through leakage from tailings management facilities. Furthermore, accidents can happen during the transport of radioactive materials, requiring actions by the operator and authorities, as discussed below.

When establishing an emergency response plan it is important to provide a clear structure and define responsibilities in order to effectively deal with emergencies. It is expected that the operator can manage emergencies on-site and provide support in the case of handling incidents occurring during transport.

Emergency response programmes typically include procedures for:

- assigning responsibilities and accountabilities;
- assessing and classifying emergencies;
- assessing source terms and consequences;
- activating and implementing emergency responses;
- notifying and alerting site personnel and other stakeholders, including the public (on-site and off-site communications);
- protecting on-site and off-site emergency response personnel;
- assembling, protecting and evacuating personnel;
- controlling exposures to radioactive and hazardous substances;
- limiting the occurrence and spread of radioactive contamination;
- responding to over-exposures, contamination incidents, injuries or fatalities;
- post-accident monitoring and assessments of systems, effluents and conditions (e.g. observations, tests, measurements, collection of samples, sample preparation and analysis, reporting results of sampling, measurements and tests);
- documenting and controlling the exchange of information;
- effecting scheduled shift changes and workplace turnovers;
- controlling vehicular and human traffic;
- directing, controlling and supporting emergency responses;
- implementing corrective actions or remedial measures;
- maintaining the security of nuclear materials.

The emergency plan may incorporate emergency preparedness and response procedures directly, or it may reference pertinent documents, such as the facility procedures manual (CNSC, 2001).

During the course of an incident it is essential to keep track of the events, monitor the effectiveness of the response and establish long-term mitigation objectives, as required.

Procedures must be carried out according to the emergency plan and instructions established during planning and training. The emergency approach and procedures used

have to be recorded in emergency response documents and consolidated through regular safety training.

A very important point when dealing with incidents related to radioactive material is keeping the public informed. This avoids inappropriate public reactions on one hand and lack of transparency criticism on the other. To this end, establishing protocols to be followed when communicating incidents to the public may be appropriate.

The requirements for emergency preparedness are defined in national regulations and are therefore country specific. In general, it can be expected that the national authorities and the operators regularly conduct assessments of threats posed by facilities.

Emergency preparedness is also part of the IAEA General Safety Requirements, defined as a measure "to ensure that arrangements are in place for a timely, managed, controlled, co-ordinated and effective response at the scene and at the local, regional, national and international level, to any nuclear or radiological emergency" (IAEA, 2002).

The IAEA provides guidance on emergency preparedness for a large spectrum of accidents involving radioactive material, ranging from radiological accidents with local (on-site) impacts to large scale nuclear accidents. These include:

- IAEA (2002), *Preparedness and Response for a Nuclear or Radiological Emergency*, Requirements GS-R-2, IAEA, Vienna.
- IAEA (2003), *Method for Developing Arrangements for Response to a Nuclear or Radiological Emergency*, updating IAEA-TECDOC-953, IAEA, Vienna.
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- IAEA (2011), *Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency*, General Safety Guide GSG-2, IAEA, Vienna.

Although these guides cannot consider all state, site or emergency-specific factors, they provide a solid basis for planning emergency preparedness.

Case study: Uranium production facilities, Kazakhstan

This case study outline's how Kazakhstan's commission for emergency investigation is prepared to provide an urgent response in the case of emergencies. The urgent response team is described as well as its role in preventing injuries and exposures to personnel and the public. A key document the uranium producer provides to prepare appropriate measures is a declaration of industrial safety that describes the character and scale of the hazards at the mine facility, activities to provide for industrial safety and readiness for action during emergency situations.

As outlined by Tyulyubayev (2012), uranium mining facilities are considered potentially hazardous objects in the frame of emergency preparedness in Kazakhstan. From this point of view emergency preparedness and industrial safety issues must form an integral part of mining practices. The specific emergency factors for uranium mining are related principally to the radioactivity of the target metal.

Policy in the field of atomic energy in Kazakhstan focuses on the safe development of the uranium mining industry, providing industrial safety and limiting radiation exposure in the mine facilities and ensuring the safe handling of radioactive materials and wastes with the aim of preventing emergency situations.

In Kazakhstan, a commission for emergency investigation has been created in order to provide an urgent response in the case of emergencies. The commission consists of representatives from the mining companies and state controlled bodies.

The purpose of the urgent response team is the prevention of injuries and exposures to personnel and the public through activities before or immediately after accidental release. The goal is to reduce exposures and limit individual doses received by the public, staff and emergency workers to levels below acceptable values.

Legislation in the field of prevention and elimination of radiation and nuclear accidents consists of basic laws covering licensing, emergency situations, atomic energy use, radiation safety, industrial safety and environmental protection. The basic principles of atomic energy policy include providing nuclear and radiation safety, accessible and objective information on the environmental effects of mining activities and impacts on local residents in a timely fashion, as well as exercising state control over mine processing.

A uranium mining company is required to:

- obtain a licence in the field of atomic energy use;
- plan and conduct activities to improve the sustainability of the operation, worker safety and public protection;
- prepare a list of potential radiation accident scenarios, including predicted effects of exposure and outcomes;
- develop a plan of activities to protect personnel and the public in the case of an emergency situation and its consequences;
- develop an accident response plan;
- develop and implement emergency preparedness measures and emergency response activities;
- either conclude an agreement with a professional rescue services organisation to cover mine maintenance or develop its own capability;
- immediately inform state agencies, the public and personnel about accidents;
- declare all mine facilities;
- maintain civil liability insurance.

Declaration

A declaration of industrial safety documents the character and scale of hazards presented by the mine, activities undertaken to provide industrial safety and readiness for action during man-made emergency situations.

A safety declaration is required in licence applications for all projected, operating or decommissioning mine facilities. It characterises the safety of the facility during all life cycle stages.

The declaration must be updated if production capacity or production techniques are significantly changed or if industrial safety requirements are undertaken at the licensed site. The declaration contains the following information:

- a list of dangerous substances and the characteristics of each;
- an account of dangerous influence factors (with each factor listed separately, in conjunction with other factors and potential environmental impacts);
- technical data on the distribution of dangerous factors;
- analysis of the dangers posed;
- technical solutions for safety provision;

- analysis of emergency situation causes;
- an account of personnel training for action in emergency situations;
- a scheme outlining accident scenarios;
- an accident response plan that includes a warning system, means and measures to protect personnel and the public, reserve resources for emergency response and medical care.

Readiness for accident elimination

One of the main issues for readiness in limiting and eliminating emergency consequences is adequate training of the workforce and rescue service personnel. Training for emergency situations includes the development and co-ordination of instructions and other guidance, distribution of this material to all potentially impacted organisations as well as providing the proper equipment and training for rescue services personnel.

Training at the mine facilities is conducted according to a plan that is approved by the territorial division of the authorised body. It is conducted under the supervision of the territorial division of the authorised body and results of the training exercise are documented in a report. Control over the implementation of proposals contained in the report is charged to the head of the organisation.

During emergency response training, the following issues are covered:

- whether all the possible accidents and their places of origin are covered in the plan;
- the efficiency of initial actions provided in the plan to localise accidents;
- the feasibility of the implementation of measures employed to save lives;
- the readiness of designated divisions for accident elimination;
- the availability of warning tools;
- the possibility of a quick escape by personnel from the danger zone (e.g. availability of emergency exits);
- the presence of emergency reserve facilities, dosimetry equipment and means of protection;
- the familiarity of personnel with rescue equipment and the ability to effectively use it;
- the co-ordination of actions among different divisions during accident elimination;
- the time required for the assembly of emergency response personnel;
- the correspondence of emergency response personnel actions to instructions and the planned response.

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3.8. Security and safeguards

Over the past years, especially after the terrorist attacks of September 2001 in New York City, nuclear security has gained importance and has turned out to be more complex than safety-related issues due to the external environment and varying threats. The main apprehensions lie in a criminal organisation obtaining nuclear materials to either create a nuclear weapon or a radiological dispersion device ("dirty bomb"), or to sabotage a nuclear facility or the transport of nuclear material.

In the case of uranium mining the main item of security interest is UOC, of which about 1 shipping container (25 barrels) or 10 tUOC is considered a "significant quantity". The term significant quantity denotes the amount of fissile material necessary to create a nuclear explosive device, although additional expertise and access to restricted facilities for processing would be required to turn UOC into a weapon. The creation of a dirty bomb from radioactive materials located at a mine site is rather unlikely and accordingly less of a security concern. Although there is radioactivity contained within the tailings, they have low activity per mass and are therefore not as easily distributed and would not be as effective as other such sources. The goal of nuclear security is to develop a concept and culture that effectively prevents such malevolent acts.

The establishment and maintenance of a good physical protection regime for nuclear materials lies in the hands of the state. It is responsible for creating the legislative and regulatory framework, designating competent authorities, providing education and training, setting responsibilities and evaluating national threats. All radioactive sources within its territory or under its jurisdiction must be identified and securely protected. The primary responsibility of the operators lies in the adoption and realisation of security measures on-site and during transport according to national requirements. Of course, the operator will also want to establish security measures to protect their other important site assets such as mobile equipment, tools, fuel, reagents, construction materials, etc.

On an international level the Convention on the Physical Protection of Nuclear Material (IAEA, 1980) provides a strategic framework and establishes standards for the protection of nuclear materials during use, storage and (international) transport. It also promotes co-operation between states to share physical protection information to facilitate fast location and recovery of illegally acquired and transported nuclear material. The convention entered into force on 8 February 1987, was strengthened through amendments in 2005 and by October 2012 comprised 148 parties.

The IAEA Safeguards provide a basis for nuclear security since confirming that relevant material is only used for its intended purpose contributes to the prevention of illegal acts. Safeguards are a set of activities undertaken by the agency to ensure that states are abiding by international non-proliferation commitments (IAEA, 2001). The IAEA monitors and verifies all source and special fissionable materials in countries under safeguards. Events in the 1990s showed that the system needed to extend beyond declared materials and activities, stimulating the development and implementation of new measures designed to improve the detection of undeclared nuclear material and nuclear-related activities. Under an Additional Protocol, a state is required to provide the IAEA with broader information covering all aspects of its nuclear fuel cycle activities, including research and development and uranium mining.

For uranium mining and processing, the following scenarios have been identified that could lead to illegal acquisition of radioactive material:

- a misuse of operating mines and mills, either by understatement of small quantities of UOC over a long period of time or theft of large quantities in a short period of time;
- misuse of closed mines, resulting in the necessity to provide adequate physical protection measures for abandoned sites;
- acquisition of uranium from sites where it is or could be produced as a by-product, as such sites might have less awareness of security issues;
- theft from processing and storage facilities or during transport.

Recommendations to achieve physical protection are provided in the 2011 IAEA publication *Physical Protection of Nuclear Material and Nuclear Facilities*. This document underscores the importance of the state in matters of nuclear security. The authorities must have good control of uranium production and need to evaluate possible scenarios of illegal acquisition and possible transport routes for unauthorised export. It is important that responsibilities are clearly assigned to operators and carriers and periodic evaluations and improvements in security measures are undertaken.

Mine operators are required to take measures that make unauthorised access to radioactive materials as difficult as possible, based on feasible risk and threat scenarios. These measures comprise:

- the establishment of limited access areas;
- detection systems against unauthorised intrusion;
- development of contingency plans to encounter malicious acts;
- familiarising state response forces with the sites.

Effective management of uranium accounting is also important so as to avoid understating uranium production and facilitating detection of insider threats. The use of established measurement and record systems, automated data entry and clearly defining responsibilities are part of an effective management system. Additionally, raising awareness on the topic and fostering development of a nuclear security culture, as well as making security staff independent from facility administration, enhance security.

The most vulnerable operation in uranium mining is probably the transport of nuclear materials, even though transport systems are designed to ensure safety. A number of measures are required to ensure security, starting with the allocation of responsibilities and carrying through to establishing procedures to report and to counter security threats. Security during transport can be enhanced by minimising the number and duration of uranium transportation events and avoiding regular transport schedules. Additionally, limiting transport information only to necessary staff reduces the risk of insider threats. However, due to the non-fissile nature of UOC, it is regarded as being of limited safeguards potential and such security requirements are generally comparatively low.

Reporting of nuclear security incidents

With growing awareness of nuclear security, the necessity of establishing an international database on illegal activities involving nuclear materials was recognised (IAEA, 2007, 2008). This led to the establishment of the Illicit Trafficking Database (ITDB) in 1995 to support the IAEA Nuclear Security Plan and improve nuclear security. Based on official reporting and publically available information the database documents instances

of nuclear material (not just UOC) detection outside of regulatory control (Hoskins et al., 2009).

As of 31 December 2012, the ITDB database contains a total of 2 331 incidents reported to the ITDB between 1993 and 2012. Loss or theft of material reported has steadily increased since the late 1990s, then declined and stabilised from about 2003 onwards (IAEA, 2013). The majority of the incidents reported involve radioactive sources used in industrial or medical applications, with the majority of industrial sources reported involve devices used of non-destructive testing, construction and mining. Of the total of over 2 000 incidents reported, a total of 91 are attributed to the illicit trafficking of natural uranium between 1993 and 2007 (Rukhlo and Gregoric, 2008). Even though the incidence of reports of this type of activity on an annual basis has been halved since the early 1990s, the continuation of reports shows that security and safeguards at uranium mines and mills can be improved even further.

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3.9. Knowledge transfer

The long-term objective of modern uranium mining is to ensure that the site of mining and milling activities, once decommissioned or remediated, will remain stable and safe for the long term. To ensure that, future generations must be fully aware of what is located where, why is it there and what must be protected or maintained, to name just a few of the key pieces of information. The key documents that summarise the operation and remediation of the site, as well as the engineered close-out design and monitoring verification programme, must be readily available in a secure location.

All of this detailed information must be archived in an information management system that is likely government controlled. Copies of that key information should also be retained by the authority responsible for long-term maintenance or security of the site. This includes issues such as ensuring that any work done at the site, for example to repair minor erosion gullies, is brought back to final design specifications. It also helps

ensure that site intrusion or disturbances do not occur, materials are not removed, that the tailings management area is not breached or disturbed and that the safety of the old mine workings is maintained.

The transfer of this site knowledge becomes a key final step for the operator or the project manager who hands over the site into the long-term care and maintenance programme. This occurs after long-term stability has been achieved and confirmed by the post-remediation monitoring programme and regulatory approval has been obtained following a final public consultation step.

As noted above under Financial Assurances, the government of Saskatchewan's Institutional Control Program includes the establishment of a registry to maintain a formal record of the closed sites, management of the funding and the performance of any required monitoring and maintenance. As an adequate archive, the registry must include and maintain the following records and information submitted by a site holder:

- location of the closed site;
- identification of the holder of the closed site;
- description of the closed site and the activities that were conducted on that site;
- the release from decommissioning and reclamation issued pursuant to *The Mineral Industry Environmental Protection Regulations* (Saskatchewan, 1996);
- reference to and the location of the documents provided by the site holder pursuant to *The Mineral Industry Environmental Protection Regulations* for the purposes of applying for hand over to the government;
- reference to and the location of a full and complete set of "as-built" reports;
- description of monitoring and maintenance obligations;
- reference to and the location of the documentation provided by the site holder when it is released from any surface lease agreement that governed the closed site (Saskatchewan, 2009).

In the case of closed uranium production facilities in former East Germany (Hagen and Jakubick, 2011), upon completion of remediation of an area or object, a final certificate is issued, which presents the basis to apply for release from regulatory supervision. Presently, with more complex objects nearing completion, the need arises to submit reclaimed areas and objects to final assessments and, as required, adjust the extent of monitoring to future uses and needs.

For the purposes of long-term stewardship it is also necessary to retain the key data on the inventory and on the "as-remediated" status of the reclaimed areas and remediated waste objects, environmental monitoring data and predictions of long-term performance with supporting documentation. The Wismut data management system is to serve as evidence of the proficiency of remedial measures and to provide support for the management of "Wismut real estate", including handling claims and liability issues, information requests (from investors, regional and community developers), public inquiries and continual adjustment/optimisation of water treatment as mine and seepage water characteristics evolve. In addition, the data bank can serve as a remediation knowledge base to help answer questions if future repairs are required.

In agreement with the regulator, a post-remediation period of five years has been foreseen by Wismut as "remediation warranty" during which the performance of the reclaimed objects in terms of erosion, geomechanical failure, direct gamma radiation, radon emission and seepage control will be monitored.

After conclusion of physical remedial works and establishment of stable conditions, the number of monitoring points and frequency of measurements can be adjusted and

reduced to the slower rate of changes typical of natural processes. The duration of the post-warranty phase monitoring is still a matter of discussion with the regulator, although recent budget planning is based on a 30-year period.

It is the policy of the remediation company in Germany, in consensus with all stakeholders, regulatory authorities, municipalities and the local public, to put the reclaimed land and remediated objects to productive use, wherever possible. A good example of the successful integration of reclamation and town redevelopment is provided by Schlema, where recreational facilities, such as the health spa, parks, promenades and a golf course have been established on a backfilled, rehabilitated and stabilised mine subsidence area and on remediated waste rock piles (Figure 3.2).

Figure 3.2. The spa park at the Schlema site (Aue), with reshaped, covered and re-cultivated waste rock piles in the background



Source: Hagen and Jakubick, 2011.

References

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Chapter 4. Conclusion and recommendations

The process of extracting raw materials to meet societal demand disturbs the environment, can put workers in potentially hazardous situations and can affect local residents. Past mining activities, conducted without adequate regulatory control, have created problems in all these areas, but over the course of the last few decades mining activities and mine development processes have significantly improved with the overarching goal of minimising all impacts. Improvements have been accomplished through the development of increasingly stringent regulatory requirements driven by societal expectations regarding the protection of people and the environment, and through industry innovation. Although all types of mining have improved, the improvements in uranium mining have been more dramatic because evolving societal expectations stemming from the serious legacy health and environmental effects of the industry have resulted in the development of strong regulatory controls. Leading practice mining companies have strived to not only meet regulatory requirements but to go beyond them.

This report provides a factual account of the wide range of improvements made in leading practice uranium mining to successfully minimise impacts today. Examples of past practices, present leading practices and the contrasting outcomes of each are provided for the main aspects of uranium mines. The application of leading practices in uranium mining outlined in this report has led to the development of one of the safest and most environmentally sound forms of mining today.

While case studies provide insights into successful management practices, it must be emphasised that the solutions developed are site-specific. Local conditions play a significant role in determining the challenges posed by mining a particular deposit, as well as in the development of effective management solutions. When mining any commodity, including uranium, a one-size-fits-all solution does not exist. Although principles and goals are broadly applicable, local site conditions play a strong role in determining the most effective management practices to minimise impacts.

Negative public perceptions of uranium mining are largely based on the adverse health and environmental impacts of outdated past practices used when uranium mining was undertaken for military purposes. The driving force, as in all types of mining at the time, was maximising production, with little regard for health, safety and the environment. This early mining period left society with serious legacies of environmental damage and health impacts on workers and, in some cases, on the public. Today, societal expectations and regulation of the industry are directed much more towards radiation protection, environmental stewardship, health and safety.

Beyond the need to maintain a mine operating licence in order to remain in business, the degree to which leading practice uranium mining companies address societal issues underlines the importance given to maintaining a social licence to mine (i.e. acceptance of the mining activity by the local population). Public consultation and stakeholder involvement have become crucial components in obtaining and maintaining a social licence to conduct mining. Put simply, public knowledge and support will facilitate the timely review and licensing of new mines. Public fear and resistance will do just the opposite.

Although this report outlines leading practices and outcomes principally to inform public debate on uranium mine development, it also provides policy makers with information on successful approaches that provide assurance that uranium mining is conducted in a safe, environmentally responsible manner. Countries currently mining or considering doing so should use the guidance provided in this report to review existing frameworks. Key components for achieving this goal are:

- establishing the appropriate regulatory framework;
- planning for closure before the mine begins production;
- requiring companies to post financial assurance to cover the costs of remediation;
- applying leading practices to minimise the radiation exposure of workers and the local population, protect water resources and safely manage and dispose of tailings and problematic waste rock;
- instituting a programme of public consultation and information sharing, beginning with an effective and all-encompassing environmental impact assessment process;
- conducting effective environmental monitoring programmes throughout the life of the mine facility.

Uranium will be an energy resource that is in demand for decades to come owing to the need to meet raw material fuel requirements for an existing and developing global fleet of nuclear power plants. New mines will be needed, in some cases in countries that have never hosted uranium mining. Key stakeholders will play an important role in facilitating the safe development, operation and closure of uranium mining operations in an environmentally responsible manner.

For countries considering hosting uranium mining for the first time, this report serves as a guide to the important regulatory and management components that are required throughout the entire life cycle of the facility. Since it takes time to develop the significant capacity required to create legislation and regulations, as well as accumulate the resources and expertise needed to effectively regulate the facilities, implementation of all the aspects outlined in this report should be adopted as long-term goals. However, the key components of life cycle mine management must be in place prior to mining.

A global market exists for this energy commodity, and although examples of the leading practices provided in this report come from a number of producers, the lack of publicly available documentation elsewhere makes it impossible to say how widely leading practices are being applied. As a result, those purchasing uranium should endeavour to determine the degree to which producers are adhering to leading practices and take this evaluation into account when making purchases. Leading practices can increase production costs giving rise to higher product costs, but the extra cost that may be incurred by sourcing from leading practice producers will help contribute to broader application of leading practice uranium mining and, in turn, to greater public acceptance of nuclear power.

Recommendations

1. Governments, industry, regulatory agencies and the public should work together effectively to make sure that leading practice uranium mining becomes normal practice in order to leave a positive legacy for future generations.
2. For countries considering uranium mining for the first time, the establishment of all life cycle components outlined in this report should be adopted as a goal and targets set for their implementation.
3. For countries currently producing uranium, the life cycle framework to manage health and environmental impacts described in this report should be taken into consideration when evaluating the effectiveness of existing frameworks.
4. Uranium producers should be open and transparent about their operations in order to provide the information necessary to evaluate practices.
5. Those purchasing uranium should ensure that uranium is preferentially purchased from producers using leading practices outlined in this report.

Annex 1. Abbreviations and acronyms

AMD/ARD	Acid mine drainage/acid rock drainage
Bq	Becquerel
CNSC	Canadian Nuclear Safety Commission
EIA	Environmental impact assessment
EIS	Environmental impact statement
EPA	Environmental Protection Agency (United States)
GEIS	Generic environmental impact statement
IAEA	International Atomic Energy Agency
ICMM	International Council on Mining and Metals
ICRP	International Commission for Radiation Protection
IRT	Initial Response Team
ISL	*In situ* leach (also referred to as *In situ* recovery – ISR)
LLAA	Long-lived alpha activity
mg	Milligram
mSv	Millisieverts
OP	Open-pit mining, also referred to as open-cast or open-cut mining
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
RDP	Radon decay product
RPP	Radiation Protection Plan
SEIS	Supplemental environmental impact statement
TLD	Thermoluminescent dosimeter
TMA	Tailings management area
TMF	Tailings management facility
tU	Tonnes of uranium metal
UG	Underground mining
UOC	Uranium oxide or concentrate
WLM	Working level months
Yr(s)	Year(s)
µg	Microgram

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Managing Environmental and Health Impacts of Uranium Mining

Uranium mining and milling has evolved significantly over the years. By comparing currently leading approaches with outdated practices, this report demonstrates how uranium mining can be conducted in a way that protects workers, the public and the environment. Innovative, modern mining practices combined with strictly enforced regulatory standards are geared towards avoiding past mistakes committed primarily during the early history of the industry when maximising uranium production was the principal operating consideration. Today's leading practices in uranium mining aim at producing uranium in an efficient and safe manner that limits environmental impacts to acceptable standards. As indicated in this report, the collection of baseline environmental data, environmental monitoring and public consultation throughout the life cycle of the mine enables verification that the facility is operating as planned, provides early warning of any potentially adverse impacts on the environment and keeps stakeholders informed of developments. Leading practice also supports planning for mine closure before mine production is licensed to ensure that the mining lease area is returned to an environmentally acceptable condition. The report highlights the importance of mine workers being properly trained and well equipped, as well as that of ensuring that their work environment is well ventilated so as to curtail exposure to radiation and hazardous materials and thereby minimise health impacts.

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