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THE URANIUM MINING REMEDIATION EXCHANGE GROUP (UMREG)

Selected Papers 1995–2007

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For further information on this publication, please contact:

Waste and Environmental Safety Section
Division of Radiation, Transport and Waste Safety
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
email: official.mail@iaea.org

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FOREWORD

The modern uranium mining industry has its origins in the rush of activity in the late 1940s as nations sought deposits of the mineral for strategic purposes. However, after the initial demand was met, the industry went into a decline. The combination of a lack of environmental protection legislation and little care being taken to minimize environmental impacts resulted in many sites being abandoned with no thought of remediation.

With the advent of nuclear power the industry had a revival during the 1970s and exploration activity surged ahead. New mines were developed, but environmental protection continued to be only an afterthought in the early days of this phase. For newer mines remediation planning became a requirement demanded ever more strongly by the authorities as the community began to express concerns about mining legacies being left for future generations to manage.

In the 1990s, two major uranium mine legacy remediation programmes were started up, one in Germany and the other in the USA. It was not long before these two groups began communicating, sharing ideas and problems with a view to exchanging data and experience in order to optimize project implementation and improve outcomes in the two countries. In 1993, a first meeting was held in the USA which the experts from both the initial partner countries found very rewarding as a means of peer review and data exchange. Further meetings followed and by 1995 invitations to participate had been extended to other groups working on similar issues in Canada and South Africa. About this time the group acquired a name — the Uranium Mining Remediation Exchange Group (UMREG). The group had no formal funding and organization was undertaken by volunteers. The group has continued to try and meet annually, usually within the framework of a larger conference or symposium which was willing to allow UMREG to ‘piggy-back’ on their organization.

By the early 2000s, much of the early work was coming to an end and there seemed to be little prospect of new activity until the funding for the remediation of other legacy sites became available. Consequently, the UMREG Executive Committee decided to assemble a selection of papers from UMREG meetings, update them where appropriate, and solicit additional invited contributions. The idea was to ensure that the accumulated knowledge would be preserved for future use.

This publication has been put together by UMREG, in consultation with the IAEA, initially as a summary record of past remediation activities. However, given the boom in uranium mining that began in 2004, it is now seen as a resource for those countries looking to remediate legacy sites in the course of redeveloping old uranium resources or for countries seeking to establish uranium mining industries and wishing to avoid the errors made previously. In both cases this publication is intended to show what lessons have been learned, from both mistakes and successes, in the business of remediating uranium mines, and to showcase potential ways forward to reduce the risk of new legacy sites being created.

The IAEA wishes to acknowledge the significant efforts of the UMREG Executive Committee: A.T. Jakubick, P.W. Waggitt and D. Metzler. The IAEA officer responsible for this publication was R. Edge of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

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EXECUTIVE SUMMARY

The end of the cold war in 1989 was followed by a massive closure of uranium mines and processing plants in the uranium producing countries of the world. The new era, the 1990s, was also marked by a global growth in environmental awareness and an increasingly stringent regulatory approach to uranium mine decommissioning and closure. These concerns also extended to remediation of legacy sites. This situation created a need for mutual exchanges of information regarding strategies and approaches applied to remediation, on a global scale. Spearheaded by the United States Department of Energy (DOE) and German Federal Ministry of Economics (BMWi), regular exchange meetings were agreed upon between the remediation programs of the two countries. Within a year or two, participation in the meetings had expanded to include other developed uranium-producing countries, initially Canada and Australia. Other countries attended on an irregular basis. These meetings were the birthplace of the Uranium Mining Remediation Exchange Group (UMREG), which has since developed to become an international network for information exchange and informal peer review for the various uranium production site remediation projects.

The first bilateral US/German meetings on remediation of uranium mining and milling legacy sites[1] were held in Albuquerque, USA (1993) and Chemnitz, Germany (1994). These meetings facilitated information exchange between groups conducting remediation projects in these countries. The exchange of ideas on remedial strategies proved mutually beneficial by introducing safe cost-efficient solutions and pragmatic administrative procedures based on sound scientific principles and proven technology.

The first multilateral meeting (with the participation of Canada and South Africa) followed in Sudbury, Canada, in 1995. Later meetings in Berlin, Germany (1995), Vancouver, Canada (1997), Denver, USA (1998), Schema, Germany (2000) and Bruges, Belgium (2001) included participation by Australia and France. By this time the meetings had acquired an identity as the Uranium Mining Remediation Exchange Group (UMREG).

In more recent meetings (Freiberg, Germany (2002, 2005, 2008), Oxford, UK (2003), and Bruges, Belgium (2007), participation has progressively increased to include representatives from uranium producing countries in Africa, Latin America, Central and Eastern Europe and Central Asia.

With the aim of promoting “economically and environmentally balanced uranium mining and remediation practices,” UMREG provides a non–commercial exchange platform for all members. Shared experiences in UMREG clearly demonstrate that low-impact mining practices integrated with environmental stewardship both minimize environmental impacts and enhance life-cycle economics of projects.

The first decade of UMREG coincided with a time of stagnant uranium markets. Indeed, in January 2001 the uranium spot market price slumped to an historic low of $18.64 per kg U. With the objective of supporting an economically and environmentally balanced approach to uranium mining and milling residues remediation, UMREG adopted a cooperative approach and served as a meeting ground for operators, regulators and other stakeholders associated with uranium mining. To keep up to date with research and development, academics dealing with relevant problems were also invited to participate in the meetings.

[1] i.e. sites at which mining practices of the past, no longer licensed today, led to environmental impacts that were left to governments to remediate.

As the uranium mining industry seems set for a renaissance in the first quarter of the 21st century a decision was made to produce a Safety Report bringing together a selection of contributions from past UMREG meetings and invited papers. The purpose of the present publication is to assist the uranium production industry, regulators and stakeholders in dealing with remediation issues of today by providing knowledge of new technology and practices and to advise of lessons learned from the past. It has been written for and by operators, regulators and other stakeholders who will hopefully find the publication useful for their work. The publication is intended to be of value to all other parties interested in the topic.

The selection of papers in the publication follows the above mentioned philosophy, based on the assumptions that:

- a further improvement of the environmental performance of uranium mining and processing is socially responsible;
- ecologically desirable; and
- economically feasible.

The remediation of uranium mining and processing legacy sites is a key factor in further development of the uranium industry, because such action is perceived by the public as the proof of trustworthiness of the uranium industry.

It should be pointed out that some of the new uranium mining activity is centred on former production areas, including some legacy sites. Such new production activities need to consider legacy remediation as part of their new resource development plans.

During the 1990s the world's two largest uranium mine remediation programs were the US DOE's Uranium Mill Tailings Remedial Action (UMTRA) Program and the Wismut Remediation Program of the German BMWi. Other, single site remediation projects went on in Canada (e.g. Elliot Lake) and Australia (e.g. Nabarlek). These "classical" remediation programs/projects pioneered the approaches to environmental remediation of the legacy wastes now being applied in many countries; and they provide the perspective of this publication as well.

It is unlikely that the "classical" approach to uranium mine and production sites remediation will continue unchanged. The expansion of uranium production activity that is presently being seen in Central Asia (Kazakhstan), North and South America, Africa, Asia and Australia is likely to benefit from the application of more advanced, exploration, mining and processing technologies, but even these are likely to have an environmental and health impacts, albeit not always in the same manner as in earlier times. A good example is the increased use of in situ leach methods (ISL) of uranium mining. Although the method may have little impact at the ground surface, it does have the potential to result in ground water contamination. This should be of concern in today's world where the water resources are frequently seen as diminishing resources under increasing risk of over exploitation.

Accordingly, an important goal for the future is to educate operators, regulators and stakeholders to:

- identify any shortcomings in the methods being used in mining and remedial operations; and
- learn to analyse environmental impacts; and, extract the scientific and technological information needed to pre-empt or mitigate hazardous situations in a timely manner.

Of particular importance for the remediation of the legacy sites in the Central and Eastern European Countries (CEEC), was the European Commissions' (EC) "Phare Programme" launched at the end of 1989. This was designed to be the European Union's (EU) financial instrument to assist the CEEC in their political and economic transition to a decentralized liberal democratic society and possible future integration into the EU. The Phare Programme expanded rapidly and by the mid 1990s included projects dealing with environmental assessment, provision of equipment and instrumentation for the assessment and preparation of remediation concepts for uranium mining and milling legacy sites in the CEEC. Phare projects for preparation of remediation of the legacy sites were implemented in seven countries (Bulgaria, Czech Republic, Estonia, Hungary, Poland, Romania and Slovenia) and by 2000 the groundwork was laid to justify financial support for implementation of remedial works.

The international approach to preparation of remediation concepts, including stakeholder involvement, was introduced early in the Russian Federation within an EU TACIS (Technical Assistance to the Commonwealth of Independent States) project designed to prepare the remediation of legacy sites at Lermontov in the Mineral Water District north of the Caucasus Mountains.

A number of Phare projects and a TACIS are featured in this publication.

Triggered mainly by decreasing supplies from secondary uranium sources, the global uranium markets started reviving after summer 2003. A steady rise in the uranium spot market price followed, surpassing the historically highest uranium price of ~US$110 per kg U in 1979/1980, and peaking at about $120 in the first half of 2007. Although no direct effect of the increasing uranium price on the remediation of the legacy sites could be registered, the resulting boom in uranium exploration activities and development of new uranium mines is certain to lead to remediation challenges, which will become visible at the stage of mine decommissioning and closure. Under the conditions of a revived uranium market the uranium industry would be well advised to use this opportunity to work alongside national governments and international organizations and among them the International Atomic Energy Agency (IAEA), to advance the cause of remediation of legacy sites.

A number of countries have benefited considerably from the recent upsurge in uranium resource development activity. Mainly they have received an increased inflow of international capital, services and technology. Due to this internationalization, and where geological conditions were favourable, some countries have abandoned conventional uranium mining altogether in favour of the latest ISL technology, with a view to increasing the efficiency of uranium production.

Considering the conditions of those countries which have recently entered the uranium market and still face the issue of legacy sites remediation it is obviously important to have a reliable scientific and technological reference basis for the new mine development and remediation projects. To address this need the publication has focused on selected topics of current interest, such as ISL, large scale relocation of tailings/waste rock and low costs uranium mine waste water treatment by construction of wetlands.

The true goal of mine remediation has been achieved if the health and environmental hazards have been contained and conditions created that facilitate future utilization of the abandoned sites, thus triggering economic development and revitalization in the region, post-mining.

As an aid to those countries where the legislative system and regulatory institutions are not yet fully developed, the publication describes the regulatory frameworks of developed uranium producing countries where the regulatory system has been in place for decades and proved to be effective. Of particular interest for the post-communist countries could be the regulatory experience from Saxony (eastern Germany), where the regulator succeeded in affecting a very pragmatic transition from the old to the new legislation concerning remediation of the uranium mining and milling sites.

An Environmental Non Governmental Organization's (ENGO) perspective of uranium mining and remediation projects has been included in the publication to emphasize the importance of a constructive dialogue between the operator and ENGOs. ENGOs can be important stakeholders because they often assume the role of advocates and advisors to concerned local citizens.

The publication presents both classical and new uranium mining and remediation projects next to each other to facilitate comparisons and stimulate cross-fertilization. The IAEA, contributors and organizers of UMREG particularly hope that the retrospective evaluations of the experience gained from the completed and mature projects and the identified deficiencies and problems in current and developing remediation projects will contribute to the advancement of the state of knowledge in uranium mining remediation and the future development of low impact uranium mining.

ANALYSES OF URANIUM RESOURCES, PRODUCTION AND DEMAND BY THE JOINT OECD/NEA-IAEA URANIUM GROUP

R.Vance[1], *J. Slezak*[2]
[1] Nuclear Energy Agency (NEA), Paris, France
[2] International Atomic Energy Agency (IAEA), Vienna, Austria

Abstract

The paper briefly describes the history, organization and activities of the Joint OECD/NEA-IAEA Uranium Group. In addition it provides a summary of the market situation for uranium as set out in the 2007 edition of the biennial report on uranium resources, production and demand, which is due for publication in June 2008.

INTRODUCTION

Since 1965, when a "Working Party" was formed to compile worldwide uranium resource estimates, the Nuclear Energy Agency (in cooperation with the International Atomic Energy Agency since the mid-1980s) has been producing detailed reports on uranium supply and demand, roughly every two years. Since all editions have had a red cover, the publication has become commonly known as the "Red Book". Over the course of its history, the Red Book (RB) has become widely recognized as the authoritative source of government-sponsored information on the industry. In total, 107 countries have contributed data to the 22 volumes published to date. The next edition in the RB ("Uranium 2007: Resources, Production and Demand") series is expected to be published in June 2008.

THE 2007 RED BOOK

The 2007 RB presents a comprehensive assessment of the global uranium supply and demand situation and includes supply and demand projections to the year 2030. Country Reports summarize recent developments in all countries that contributed to the development of this edition of the RB, including updates of recent exploration and mine development activities as well as descriptions of ongoing programs in environmental activities in the industry.

Market conditions are the primary driver in the development of uranium production capability. Many aspects of the current market have been shaped by a 20 year period of low prices for the metal (1983-2003) that followed a period high prices and intense exploration and production during the 1970s and 1980s. Since production in the early years of the industry greatly exceeded subsequent requirements, a large inventory was accumulated. This inventory of so-called "secondary supply" was an important factor in keeping prices low. Two decades of low prices resulted in the closure of all but the lowest cost mining facilities, stimulated market consolidation and curtailed investment in exploration and mine development.

At the end of 2007, the spot price of uranium stood at about $235/kg U, up considerably from the historical low of a little over $18/kg U established in late 2000. As market prices have been increasing and expectations of a sustained price increase were developing, plans for significant new production is taking shape, particularly in Australia, Canada and Kazakhstan. Exploration and mine development activity is intense for the first time since the early 1980s. The industry is now trying to catch-up from an extended period of under investment.

Resource figures are dynamic and related to commodity prices. Resource figures presented in the RB are a “snapshot” of the situation as of the particular year that data were gathered. Not surprisingly, global exploration and development expenditures increased many-fold in recent years as the market strengthened, particularly after 2003. As exploration expenditures have been increasing, so too have uranium resources. Identified resources have already increased from 2005 to 2007 by an amount sufficient to power the global nuclear power reactor fleet for 11 years, at current rates of consumption. Should favourable market conditions continue to stimulate exploration, additional discoveries can be expected, just as periods of heightened exploration effort have in the past.

Although uranium exploration and mine development activity has responded to the improved market conditions, uranium production has not yet increased. In fact, uranium production declined by about 6% between 2006 and 2005, principally owing to a combination of lower than expected ore grades, extreme weather events and technical difficulties at mines in Australia, Canada, the Russian Federation and South Africa. While overall production declined, increased production was recorded in Kazakhstan, the United States of America, Niger and Uzbekistan.

As the inventory of “secondary sources” declines and prospects for growth in nuclear generating capacity improve and demand for uranium increases, there will be additional pressure for mine expansions and new mine development to proceed rapidly. This pressure to increase production will have to be achieved with the widespread use of best practices to minimize environmental impacts associated with uranium mining, milling and nuclear fuel production. As documented by UMREG activities, environmental issues associated with mining practices of the past have left several governments with large expenditures to remediate these old mines and have undermined public confidence in today’s uranium mining companies. Uranium Group members are aware of the necessity to not repeat this experience. Through updates of environmental activities provided in the Red Book and collaboration with UMREG, efforts are being made to inform all of the need for the widespread use of best practices in environmental management to ensure that the coming generation of uranium mines are opened and closed in a cost-effective and publicly acceptable fashion.

STATE AND PROSPECTS OF CLOSURE AND REMEDIATION OF TAILINGS DEPOSITS FROM URANIUM ORE PROCESSING AND HEAP LEACHING IN EUROPE

R. Hähne[1]*, S. Murphy*[2]*, J.Vrijen*[3]
[1] C&E Consulting und Engineering GmbH, Chemnitz, Germany
[2] The European Commission, DG Energy and Transport, Luxembourg
[3] KARUWEEG BV, Middelburg, the Netherlands

Paper presented within the International Mining Symposium WISMUT in Gera/ Germany September 10 to 12, 2007, invited by UMREG 2008 for IAEA

Abstract

Nearly sixty years of uranium mining and milling in Europe has resulted in more than 7000 environmental liabilities. Among them are 87 tailings sites at 63 different locations, spread over 12 European Countries. These 87 sites contain 314 million m³ tailings and cover a whole area of 2530 hectares. 61 sites are resulting from milling and 26 sites from heap leaching. Four tailings ponds are still in operation, 40 sites were remediated and 22 are in ongoing remediation. Based on an inventory and a study, established by an international team of experts engaged by the EC, for the enlarged EU the best remediation practice, the country specific planning procedure, the legal conditions, the radiological criteria, the remediation costs, the responsibility for remediation, maintenance, surveillance and the involvement of public are described.

INTRODUCTION

Nearly sixty years of uranium mining and milling in Europe has resulted in a variety of smaller and larger environmental liabilities in several of the EU Member States.

Uranium mine and mill tailings is a type of low activity waste containing long-lived radionuclides (half-life greater than 30 years), which may require special attention within a country’s overall radioactive waste management framework. Many of these Member States have been involved in uranium mining.

Uranium mining usually results in large volumes of waste rock piles at the surface without any uranium concentrations of concern or with only very low uranium concentrations. In addition, these waste rock piles are positioned very close to the shafts and adits of the mines where the ore extraction has taken place. The volume of these waste rock piles can vary between a few thousand and several tens of millions m³.

Some of these Member States have not only been involved in uranium mining but also in uranium ore processing to extract the uranium from the mined ore. This processing can have been physical processing or chemical processing. In these countries one finds as residues of these activities the typical mine or mill tailings.

Different types of tailings from uranium ore processing are:

- Residues from physical processing of ores (hand picking, radiometric sorting, gravitational sorting) from early days of uranium production (to 1960`s), disposed of as piles, dumps or backfill of open pits;
- Residues from chemical processing (acidic or alkaline), disposed of as slurries in open pits, basins, half basins or storages in valleys; and

- Residues from heap leaching (acidic or alkaline), disposed of at location of leaching or relocated to dumps, open pits or ponds.

Many of these uranium mine and mill tailings disposal sites were constructed and operated in the years when health risk assessment and environmental concern played a less pronounced role than they do today.

As a consequence of a growing awareness of the National Authorities over the last two or three decades, and supported by an increased public concern, closure of processing activities led not only to closure of tailings deposits but in most cases also to the necessity to remediate these tailings deposits in order to reduce their impact on health and environment to acceptable and sustainable levels.

Unfortunately, the costs of rehabilitation of mine and mill tailings are extremely high – relative to the income that has been generated by the uranium production itself. The situation is even worse in those cases where the uranium production has ceased and the mines and mills are abandoned, especially where the companies have ceased to operate or even exist. In those cases, the responsibility for rehabilitation as well as for its financing falls to the State.[1]

THE PURPOSE OF THE INVESTIGATION

In 2005/2006 the European Commission, DG Energy engaged a team of experts from the companies C&E/ Germany, BS/ Germany and KARUWEEG/ the Netherlands to establish a detailed overview of the situation concerning uranium mine and mill tailings in the recently enlarged European Union (27 Member States).

More specific, the study had:

- to establish for each of the involved countries a detailed overview of the actual situation concerning uranium mine and mill tailings;
- to establish an overview per country of the activities being undertaken to remediate these problems and to rehabilitate these areas; and
- to identify the best practices applied and the estimated costs to complete all remediation activities.

The environmental legacy of sixty years mining and milling of uranium ores in Europe consists of more than 7000 liabilities, needing care and attention. A special group amongst all these liabilities is the uranium mine and mill tailings disposal sites.

There have been 87 of these mine and mill tailings deposits within 63 different sites in operation over the years. They are spread over 12 countries in Europe: Bulgaria, Czech Republic, Estonia, France, Germany, Hungary, Poland, Portugal, Romania, Slovenia, Spain and Sweden (Figure 1).

This study has only assessed the situation concerning these 87 identified mine and mill tailings deposits.

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[1] The technical details of the legacy sites remediated within the European Union are provided in the attachment "REVIEW OF THE EUROPEAN LEGACY SITES".

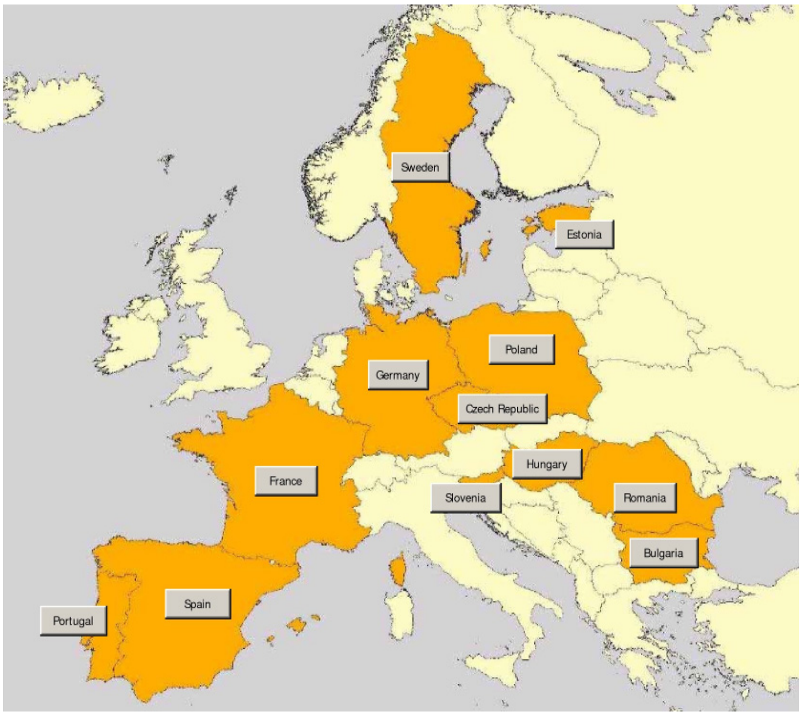


FIG. 1. Countries of the enlarged EU with uranium mining and/or milling.

ITEMS OF CONCERN

For all these mine and mill tailings the following items of concern were investigated:

(1) Tailings inventory at the sites and installations, where activities of uranium ore processing activities are or were carried out; status of the sites with respect to completed and/or ongoing environmental protection measures (e.g. stabilization, waste water collection and treatment, covering of tailings against wind erosion, limitation of radon exhalation and rain water infiltration, enclosure of tailing deposits to prevent admittance of the public, etc.).
(2) Information provided to the public and the officials with respect to the contamination levels, pollution transport, quality of environmental media and ongoing or planned protection measures; risk perception by the public and the authorities in relation to risk assessments performed by operators or experts.
(3) Results and distribution of pollution monitoring (ground and surface waters, contaminated dust and radon in air, displacements of contaminated material) and their dependence on ongoing production respectively closure activities.
(4) Financial (grant) systems for the remediation of tailings ponds or heaps and also with respect to decontamination and rehabilitation of contaminated surrounding areas (e.g. factory areas, transport routes, running waters etc.).
(5) Technical solutions and costs of the waste management and of the remediation of tailings ponds or heaps and of the rehabilitation of contaminated surroundings.
(6) Legal requirements and criteria for the health protection of the public (especially radiation protection) and the environment and the technical aspects of protection measures.
(7) Site specific remediation objectives established for the closure and rehabilitation of the uranium mining and milling sites; assessment of compliance of these objectives with respect to planned future reuse of the sites and their surroundings.

(8) Responsibilities for the long term surveillance after closure of the facilities and after the realisation of all remediation measures; engagement of the authorities and obligations of future users of the sites in the long term environmental monitoring.
(9) Consideration of possible special cases such as "the former owner/operator went out of business without remediating and restoring the area" or "conversion of tailings ponds or heaps into more general repositories of radioactive wastes".

OVERVIEW OF THE URANIUM MINE AND MILL TAILINGS IN EUROPE AND THEIR ACTUAL STATUS OF REMEDIATION

An overview of the uranium mine and mill tailings disposal sites in Europe and their distribution amongst the involved countries is presented in Table 1 and Figure 2.

TABLE 1. OVERVIEW OF THE COUNTRIES, INVOLVED IN THE STUDY, THE NUMBER OF URANIUM MINE AND MILL TAILINGS DISPOSAL SITES AND THEIR STATUS OF OPERATION

Country	Number of uranium mill tailings disposal sites		Number of uranium mine tailings (heap-leaching) no longer in operation (i)	Total number of uranium mine and mill tailings disposal sites
	still in operation	no longer in operation		
Bulgaria (BG)	0	2	6	8
Czech Rep.(CZ)	3	7	0	10
Estonia (EST)	0	1	0	1
France (F)	0	13	8	21
Germany (D)	0	22	1	23
Hungary (HU)	0	2	1	3
Poland (PL)	0	1	0	1
Portugal (P)	0	2	7	9
Romania (RO)	1	1	0	2
Slovenia (SLO)	0	1	0	1
Spain (E)	0	4	3	7
Sweden (S)	0	1	0	1
Total	**4**	**57**	**26**	**87**

(i) Today there are no heap leaching sites in operation in Europe

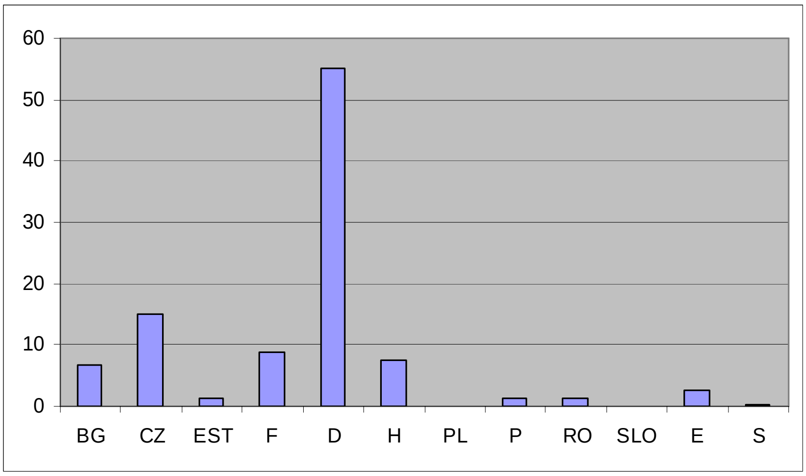


FIG. 2. Distribution of volumes of tailings in the enlarged EU (%).

D:	55% of tailings volume of EU
CZ, F, H, BG:	38% of tailings volume of EU
E, RO, EST, P:	7% of tailings volume of EU
S, SLO, PL:	0.4% of tailings volume of EU.

Concerning the technological origin the tailings are divided as follows:

- Physical processing: approx. 6 million m³ tailings (2% of total volume) cover 120 hectares (5% of total area);
- Chemically processing: approx. 280 million m³ tailings (90% of total volume) cover approx. 2190 hectares (85% of total area); and
- Heap leaching: approx. 24 million m³ tailings (8% of total volume) cover over 250 hectares (10% of total area).

All information that has been collected and verified has – as far as relevant for the purpose of this study – been incorporated in a database on the present situation in the countries involved. This database contains the information per object, per site and per country.

In total these 87 tailings sites within 63 locations contain approximately 314 million m³ of uranium mine and mill tailings, covering an area of 2530 ha in total. Their individual volumes range from less than 0.1 million m³ to more than 60 million m³ per site. Most of these 87 tailings sites are closed by now. Only four remain in operation at this moment: three in the Czech Republic and one in Romania. Of the other 83 tailings deposits, 40 have already been remediated completely (Figure 3). Another 22 tailings sites are currently under remediation and for the last group of 21 tailings sites the remediation still has to start.

In most cases the tailings sites in the enlarged EU do not have an intolerable impact on environment and health and in only a few cases (Bulgaria, Estonia) can cross-border impact of their risk not be excluded before the remediation will be finalized.

FIG.3. Example of the remediation of a mill tailings site (Eleshnitsa/Bulgaria).

REMEDIATION PLANNING

In the past, the primary objective for remediation of these tailings deposits was always to provide covering for sealing–off and shielding of the deposit. Sometimes it was even the only objective. These days, conceptual remediation planning takes place in a more structured manner: looking first to the risk factors concerning a specific site and its location and surroundings. Thereafter risk mitigation is translated into technological remediation steps.

In addition, when designing cover systems, much more emphasis is given to long term stability and also to long term performance; not in the last place to prevent future environmental problems by loss of integrity, due to wear or neglect. Engineering approaches and modelling tools have developed significantly in this direction over the last 30 years or so.

In this respect it also appears that the size of a site does not fundamentally change the methodology for its conceptual remediation planning. Not even when the difference in size is a factor of 100 or even more.

It seems that the various pilot projects on systematic remediation planning and on the transfer and training of western technical tools, implemented from 1996 until 2000 in the nine countries of the Eastern Europe, within the Phare Multi-Country Programme for

Environment, have been integrated well by the beneficiaries in their own conceptual and detailed remediation planning.

"BEST" REMEDIATION PRACTICE

It does not appear meaningful to identify something like "best remediation practice" for all facilities and sites, since every site is unique in many respects and climate, geology and topography have an important effect on what is necessary, what is sufficient and what is excessive. But the systematic methodology in close relation with locally available technical means (such as materials) and constraints (such as space, discharge limitations) can result at each object in "Best Practice" as is clear in many cases.

It is observed that a clear conceptual planning for disposal site remediation is still not developed for the uranium mine and mill tailings disposal sites in Romania and Portugal. These countries might benefit in their preparations from knowledge currently implemented in the rest of Europe.

REMEDIATION COSTS

Remediation costs for uranium mine and mill tailings disposal site remediation are always high. Costs for remediation of these uranium tailings disposal sites vary between €1 and €20/m³ in the countries investigated, depending strongly on their site's individual size and complexity. In comparing these data it should be recalled that the already quite substantial remediation costs in the newest Member States are mostly based on the costs for local labour, for local materials and for local transport. In most of these countries these costs would need to be multiplied by a factor 4 to 8 in order to make their costs comparable to those for similar remediation activities in the countries of Western European.

This made it necessary in the past to arrange for external financial support for economically weak countries such as Bulgaria or for countries with relatively small populations, such as Estonia. This (limited) financial support also appeared to be a highly efficient instrument to achieve adequate and complete solutions in these countries and to have them implemented in a well-controlled and cost-efficient manner.

It is observed that in some other countries like the Czech Republic, Romania and Slovenia and perhaps also for Portugal providing similar financial support might trigger these countries to adjust their environmental and financing priorities in a similar manner as achieved in the first-mentioned countries. This could be highly beneficial for minimising their exposure consequences as well as their total remediation costs over time.

RESPONSIBILITIES FOR PLANNING REMEDIATION AND FOR IMPLEMENTING THE MEASURES

Splitting of responsibilities concerning design, construction and quality control is implemented already in some of the countries investigated, but not in all. In some it still retained by a single operator.

As observed from some experiences in the past, this does not always lead to the intended quality of results. From a quality management point of view it would represent a significant improvement to use independent experts for the supervision of implementation as well as to choose for independent monitoring.

LONG TERM MONITORING, SURVEILLANCE, MAINTENANCE AND INSTITUTIONAL CONTROL

Nearly all uranium mine and mill tailings are remediated in situ. Only a few were relocated to be combined with similar disposal sites. The reason for these disposal solutions is financial. Considering the very large volumes involved, the costs for underground disposal of these wastes would be extremely high.

However, considering the large quantities of long-lived radioactive materials the lifetime of these facilities and sites, in which they have to be kept secured from environmental and human interference, runs easily into periods of hundreds of years or even longer. This is reflected in the design basis for the technical solutions, which in many countries is set also for some hundreds of years. Institutional solutions are needed to ensure that over the years such technical solutions stay in place as they were designed and constructed. It was observed that the responsibilities for implementing the technical remediation measures (the current situation) are fairly well organized.

However the policy lines for institutionalizing formal stewardship, to care properly for long term monitoring, surveillance, maintenance and institutional control for these hundreds of years to come are not clear at all.

DIFFERENCES IN THE REGULATORY SYSTEMS

It is observed in countries where mining laws were applied for the licensing of mining activities, that these laws were also used for the licensing of the ore extraction activities and even for the licensing of the uranium mine or mill tailings disposal site remediation activities.

In itself this is acceptable but in those countries where this is standing practice the involvement of the public and other interested parties is not organized as well as it is in those countries where licensing is via the environmental legislation, leading to the requirement to carry out a full environmental impact assessment, in accordance with the EIA Directive.

COMMUNITY LEGISLATION

In the past there was no clear guidance from community legislation on which legal tools had to be applied for the remediation of uranium mine and mill tailings disposal sites. Apart from radiation protection guidelines and directives for waste management, a rather wide range of quantitative criteria has been developed in the respective countries, for instance for regulating permissible discharge water pollution limits, for quality requirements of sealing covers, etc. This has resulted in considerable variety in discharge limit values. In Estonia – due to the lack of other quantitative guidance – the EC Landfill Directive has been adopted by the Ministry for Environment in order to derive acceptable and defendable criteria for seepage water discharge limits and for limits in environmental contamination.

It is expected that more harmonization will be achieved when the new Council Directive on waste from the ore extraction industry comes into force following its ratification in the National Parliaments. However it might prove necessary to follow-up on the implementation of this EC Directive in the national legal framework, as relevant for the uranium mine and mill tailings under remediation now or in the future.

RADIATION PROTECTION CRITERIA

From a radiation protection point of view the basic dose criteria applied in the various investigated countries do not differ very much and comply, with respect to the dose to the public, with the Council Directive 96/29/Euratom of 13 May 1996. The effective dose of the public owing to emissions from the disposal sites is in general limited to 1 mSv/y. In France, where at the time of remediation a higher dose criterion was applied (5 mSv/y), it was later demonstrated that the performed remediation complies also with the 1 mSv/y criterion.

At this moment there seems to be no need for further harmonizing of radiological criteria used in the countries involved in the remediation of uranium mine and mill tailings disposal sites.

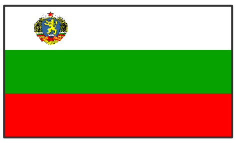
PUBLIC INVOLVEMENT

It would seem that the local population was always well informed, even in the former "secret years" of uranium mining and extraction. Nowadays in all countries that provided information about their communication methods, it is quite clear that all apply a more or less similar open information policy. However, there is a difference between those countries that apply the obligatory EIA system, with clearly defined rights of involvement for the public and other countries that only request that the public is informed. This difference in rights for the public could be eliminated by making an EIA obligatory in the planning and implementation of remediation measures for uranium liabilities with a significant impact on health and the environment.

It was remarkable how quickly the role and activities of the Media in the former Eastern-European countries developed over the last 10–15 years and how similarly with their counterparts in Western European countries they operate nowadays with respect to this issue, despite their different histories and cultural background.

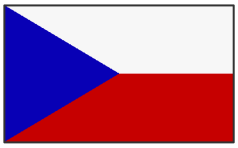
OVERVIEW OF THE URANIUM MINING AND MILLING WASTE SITES IN THE EUROPEAN UNION

Uranium Mine and Mill Tailings Sites in Bulgaria



Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings (ha)
BG-01	Buhovo Seslavtzi	Heap leaching	1955-92	finalized	0.03	2.4
BG-02	Buhovo TP	Mill tailings	1956-92	ongoing	10.0	188
BG-03	Byalata voda	Heap leaching	1985-91	finalized	0.11	1.86
BG-04	Dospat - Barutin	Heap leaching	1957-84	finalized	0.50	12
BG-05	Eleshnitsa Kremen	Heap leaching	1986-89	finalized	0.012	0.36
BG-06	Eleshnitsa Zvesda TP	Mill tailings	1963-92	ongoing	10.3	42
BG-07	Smolyanovtzi	Heap leaching	1985-90	finalized	0.012	0.66
BG-08	Smoljan Teklen	Heap leaching	1984-91	finalized	0.06	0.04

Uranium Mine and Mill Tailings Sites in Czech Republic



Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings (ha)
CZ-01	Jachymov Elias	Mill tailings	1947-62	closed, no plan	0.9	15
CZ-02	Mydlovary KI	Mill tailings	1962-84	ongoing	5.6	26.2
CZ-03	Mydlovary KIII	Mill tailings	1980-85	ongoing	4.35	39.8
CZ-04	Mydlovary KIV	Mill tailings	1967-91	ongoing	12.5	211.5
CZ-05	Nejdek	Mill tailings	1952-64	closed, no plan	0.85	12.3
CZ-06	Pribram KI	Mill tailings	1959-91	closed, no plan	0.2	33
CZ-07	Pribram KII	Mill tailings	1980-88	finalized	0.2	13
CZ-08	Rozna KI	Mill tailings	ongoing since 1968		9.7	64.5
CZ-09	Rozna KII	Mill tailings	ongoing since 1980		1.5	27.4
CZ-10	Straz I and II etapa	Mill tailings	ongoing since 1979		11.3	187

Uranium Mine and Mill Tailings Sites in Estonia

Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings (ha)
EST-01	Sillamäe	Mill tailings	1959 - 2003	ongoing	4	40

Uranium Mine and Mill Tailings Sites in France

Ident number	Object	Type of object	Operation period	State of remediation	Mass of tailings (million tons)	Area tailings (ha)
F-01	Bauzot	Mill tailings	1950-85	finalized	0.0056	
F-02	Bellezane	Mill tailings	1988-93	finalized	1.5	10
F-03	Bertholene	Heap leaching	1984-95	finalized	0.476	
F-04	Bessines	Heap leaching	1958-87	finalized	8.6	
F-05	Bessines	Mill tailings	1958-87	finalized	11.4	33.5
F-06	Bois Noirs Limouzat	Mill tailings	1955-80	finalized	1.3	18
F-07	Gueugnon	Mill tailings	1955-80	finalized	0.22	6
F-08	Jouac	Mill tailings	1978-2001	finalized	1.9	36
F-09	L' Ecarpiere	Heap leaching	1967-91	finalized	3.8	
F-10	L' Ecarpiere	Mill tailings	1957-91	finalized	7.5	72.7
F-11	La Commanderie	Heap leaching	1955-91	finalized	0.25	
F-12	La Ribiere	Heap leaching	1982-85	finalized	0.2	
F-13	Le Bouchet	Mill tailings	1946-70	finalized	0.028	0.95
F-14	Le Cellier	Heap leaching	1965-90	finalized	4.1	
F-15	Le Cellier	Mill tailings	1965-90	finalized	1.7	
F-16	Lodeve	Mill tailings	1975-97	finalized	4.1	54
F-17	Montmassacrot	Mill tailings	1987-90	finalized	0.74	2.6
F-18	Rophin	Mill tailings	1950-55	finalized	0.03	2
F-19	St Pierre du Cantal	Heap leaching	1958-85	finalized	0.535	
F-20	St Pierre du Cantal	Mill tailings	1958-85	finalized	0.07	
F-21	Teufelsloch	Heap leaching	1954-63	finalized	0.004	

Uranium Mine and Mill Tailings Sites in Germany

Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area
D-01	Aue Hakenkrümme	Mill tailings	1953-57	closed, no plan	0.56	5.8
D-02	Borbachtal	Mill tailings	1948-97	finalized	0.28	8.2
D-03	Helmsdorf	Mill tailings	1958-89	ongoing	50	205
D-04	Culmitzsch A	Mill tailings	1967-91	ongoing	64	158
D-05	Culmitzsch B	Mill tailings	1967-91	ongoing	24	84
D-06	Dänkritz 1	Mill tailings	1952-58	ongoing	4	20.5
D-07	Dänkritz 2	Mill tailings	1955-58	planned	0.89	6.5
D-08	Freital 1	Mill tailings	1949-55	closed, no plan	0.45	5.1
D-09	Freital 2	Mill tailings	1955-57	closed, no plan	0.2	1.7
D-10	Freital 3	Mill tailings	1955-57	closed, no plan	0.21	3.4
D-11	Freital 4	Mill tailings	1958-60	closed, no plan	0.5	5.4
D-12	Gessen	Heap leaching	1975-89	finalized	3	12
D-13	Gittersee A	Mill tailings	1953-62	finalized	2.1	20
D-14	Gittersee B	Mill tailings	1961-62	finalized	0.33	7.3
D-15	Johanngeorgenstadt 1	Mill tailings	1949-53	closed, no plan	1.15	8.6
D-16	Johanngeorgenstadt 2	Mill tailings	1953-56	ongoing	0.35	8
D-17	Lengenfeld TP	Mill tailings	1950-61	finalized	1.0	14
D-18	Lengenfeld Plohnbach	Mill tailings	1950-54	planned	0.1	11
D-19	Oberschlema	Mill tailings	1949-53	finalized	0.4	5
D-20	Schneckenstein 1	Mill tailings	1952-57	ongoing	0.6	4.5
D-21	Schneckenstein 2	Mill tailings	1948-52	ongoing	0.1	1
D-22	Trünzig A	Mill tailings	1961-67	ongoing	13	66.8
D-23	Trünzig B	Mill tailings	1961-67	ongoing	6	41

Uranium Mine and Mill Tailings Sites in Hungary

Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings
H-01	Pécs TP 1	Mill tailings	1962 - 1997	ongoing	15.8	100
H-02	Pécs TP 2	Mill tailings	1979 - 1991	finalized	4.6	60
H-03	Pécs HL 1	Heap leaching	1966 - 1995	finalized	3.6	47

Uranium Mine and Mill Tailings Sites in Poland

Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings (ha)
PL-01	Kowary	Mill tailings	1967 - 2000	finalized	0.09	1.9

Uranium Mine and Mill Tailings Sites in Portugal

Ident number	Object	Type of object	State of remediation	Volume tailings
P-01	Bica	Heap leaching	planned	0.037
P-02	Castelejo	Heap leaching	planned	0.032
P-03	Cunha Baixa	Heap leaching	planned	0.248
P-04	Forte Velho	Heap leaching	planned	0.002
P-05	Quinta do Bispo	Heap leaching	planned	0.545
P-06	Rosmaneira	Heap leaching	planned	0.009
P-07	Senhora de Fontes	Mill tailings	planned	0.027
P-08	Urgeirica Barragem	Mill tailings	planned	2.8
P-09	Vale d`Arca	Heap leaching	planned	0.005

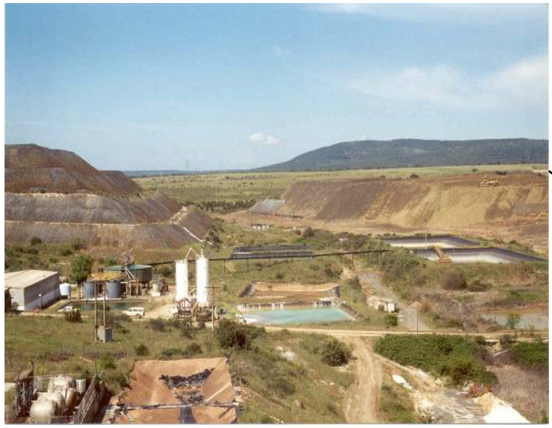
Uranium Mine and Mill Tailings Sites in Romania

Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings (ha)
R-01	Feldioara TP-1	Mill tailings	from the fifties till a few years ago	closed, remediation not started yet	> 4	44
R-02	Feldioara TP-2	Mill tailings	ongoing		not known	not known

Uranium Mine and Mill Tailings Sites in Slovenia

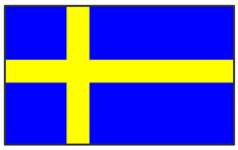
Ident number	Object	Type of object	Operation period	State of reme-diation	Volume tailings (million m³)	Area tailings (ha)
SLO-01	Zirovski Vrh	Mill tailings	1984 - 1990	ongoing	0.35	4.1

Uranium Mine and Mill Tailings Sites in Spain



Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings (ha)
E-01	Elefante	Heap leaching	1975-93	finalized	3.5	34
E-02	Elefante	Mill tailings	1975-93	finalized	0.5	80
E-03	Fabrica de Uranio de Andujar	Mill tailings	1959-81	finalized	0.98	94
E-04	Lobo-G-La Haba	Heap leaching	1981-90	finalized	0.15	5
E-05	Lobo-G-La Haba	Mill tailings	1981-90	finalized	0.1	4
E-06	Quercus	Heap leaching	1993-2000	planned	0.75	80

Uranium Mine and Mill Tailings Sites in Sweden



Ident number	Object	Type of object	Operation period	State of remediation	Volume tailings (million m³)	Area tailings (ha)
S-01	Ranstad	Mill tailings	1965-1969	finalized	1.0	25

URANIUM MINING LEGACIES IN CENTRAL ASIA: AN OVERVIEW

O.Voystechovich[1], N. Kurylchyk[2], P. W. Waggitt[2], A. T. Jakubick[3]
[1] Hydromet Institute, Kiev, Ukraine
[2] IAEA, Vienna, Austria
[3]Wismut GmbH, Chemnitz, Germany

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Abstract

The uranium mining and milling operations of the former Soviet Union undertaken in Central Asia have left a significant series of legacy sites that area major cause of public concern. The paper describes the current situation and how various agencies, including the International Atomic Energy Agency, are working with each other and the Governments of the States involved towards the alleviation of the problems caused by these sites.

INTRODUCTION

Uranium mining and milling was an important and intensive industry in most of the Central Asian countries of the former Soviet Union. During the 1970s and 80s, more than 30% of the total uranium production of the USSR came from the Central Asian countries. The mining and milling technologies applied for uranium production were uniform, designed and developed by the same engineering unit attached to the Ministry of Medium Scale Machine Industry. Accordingly, the characteristics of the uranium mining legacies in Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan (as well as in Russian Federation, Ukraine and East European countries) are essentially identical. It has left a legacy of radioactive residues. Development of most of the uranium deposits in Uzbekistan, Tajikistan, and Kyrgyzstan and partially in Kazakhstan was stopped after collapse of the former Soviet Union. All of these countries found themselves facing the problem of safe management and remediation of many sites affected by operation of uranium mining and milling facilities.

After these countries became independent, the issues of restructuring and decommissioning of the mines and other uranium facilities arose at the same time. Their common problem is also a lack of previous experience in safety assessment and remediation planning. National experience in development of environmental monitoring and analytical capacities of most laboratories which were in charge of monitoring programs at legacy sites and other areas of concern was also very limited.

Therefore the Member States expressed their interest in receiving advice and technical assistance towards building up capacity for key national laboratories and cleaning up the legacy of former uranium mining and milling activities, aiming to protect their population and environment. Following requests from several Central Asia Member States, the IAEA offered the regional project (TC RER9086) and a number of national projects for improving cooperation between and within these countries. The form of project assistance included workshops, scientific visits to advanced projects in other countries and expert advice regarding improvements of the national legislation, provision/upgrading of sampling and analytical equipment, and training of the management and laboratory staff. The IAEA's experts also assisted the Member States in the following work areas: evaluation of the current status of the former uranium facilities; in development of regulatory framework and environmental monitoring programs; assessing the radiological impact of residues at the former uranium mining and milling sites and evaluating the remediation works already underway.

STATE OF THE LEGACY SITES

Tajikistan

Mining is an important sector of the economy in Tajikistan. The past development of the uranium mining and processing led to an accumulation of large amounts of wastes from these facilities. Uranium ores mined in the country and imported from other countries were processed here. The processing was carried out by the former Leninabad Geochemical Combine (currently State Enterprise (SE) “Vostokredmet”) and also by other hydro-metallurgical plants located in the vicinity of uranium ore extraction sites (Adrasman, Taboshar, Isphara etc.). The legacy wastes of uranium mining/milling contain a high content of radionuclides (of the uranium-thorium series) and of other hazardous substances. The legacy sites are often located close to residential areas or in the upper parts of the main watersheds, such as in the Fergana Valley of the Syr-Daria River.

SE “Vostokredmet” estimates the total amount of residual uranium in the tailings and waste rock piles left behind in the Republic of Tajikistan to be approximately 55 million tons. The total activity of these wastes corresponds to approximately $240\text{-}285 \times 10^{12}$ Bq. More than 170 million tons of waste rock piles and tailings were left in the vicinity of former hydrometallurgical plants and chemical-leaching sites.

The present containment of the waste rock piles and tailings at the Taboshar, Adrasman and Degmay (close to Chkalovsk) sites must be considered as inadequate. The tailings deposit at the Degmay site is without water or other protective cover. The pond water evaporated due to arid climatic conditions long time ago and the surface of the tailings is badly cracked causing a high Rn–222 exhalation (36–65 Bq $m^{-2}s$). The ambient concentration of Rn–222 on the site varies from 200 to 1000 Bq m^{-3}. A significant amount of contaminated dust is continuously resuspended from the tailings surface. The contamination of the ground water in the vicinity of the Digmay site by sulphates and radionuclides is currently under assessment. The design and location of the new observation wells and the restoration of the existing monitoring network on the site is assisted by the IAEA. Although no final remediation strategy is yet in place for the Digmay tailings, the covering of the tailings with the indigenous soils from the shore of the tailings pond could provide an acceptable solution. However, the Degmay remedial plan is part of the overall remediation solution involving other sites, such as the remediation/re-utilization of the uranium tailings near Chkalovsk.

FIG.1. Degmay tailing surface cracked.

The state of the uranium tailings at the Taboshar site was appraised by the IAEA experts. Millions of tons of crushed/milled low grade uranium ore found to have been accumulated in the vicinity of the town of Taboshar. The pile was never stabilized and/or covered and is subject to continuous erosion. Although the tailings located at the lower levels of the slope have been covered, the cover is inadequate and has been damaged by burrowing animals. Possible remedial strategies for the various mine/mill waste piles on the site include repair of the existing covers, construction of new covers or relocation of the waste into the neighbouring open pit, the former uranium mine. If a relocation strategy should be selected for the remediation of the Taboshar site valuable use could made of the Wismut experience with large scale relocation of waste rock piles into the open pit mine of Ronneburg.

FIG. 2. Low-grade milled ore pile in the vicinity of Taboshar town.

The radon exhalation and dusting of radioactive particles from the waste piles presents no immediate risk for the population of the city of Taboshar because the area is well ventilated. However, the large amount of mine and mill waste materials, inadequate pile cover, a large open pit mine flooded with water and a shallow groundwater level in the area facilitate the contamination of the surface and ground waters by seepage from the piles and drainage from the mine, which is subsequently used by the local population and domestic animals.

A very specific case for this region was with tailing pore water leaching, which was found at the foot of the tailings I and II located at the hill of mountain slope at Taboshar. The tailings seepage waters, with very high sulfate (SO_4 9200–9600 mg/l), carbonates (HCO_3 1780–1800 mg/l), very high uranium (^{238}U 53–74 mg/l) and low radium concentration in solution, were observed in the creek's waters inlet to the mountain river near Taboshar town. The seepage water discharges are relatively high during wet and cold seasons and very low during summer period according to the underground water table elevation seasonal changes; they also inundate the tailing body. Due to hot climate conditions the drainage waters evaporating on the runoff are, and carbonate, sodium and sulphate complexes of uranium are precipitating to the base of the pile, creating a white salt cover with yellow uranile crystals. The concentrations of ^{238}U in salt complexes are 10–20 Bq g^{-1}; an efficient secondary re-extraction of uranium might be possible from such precipitates.

FIG.3. Uranium salt precipitates on the bottom of the creek that receives the seepage from the low grade ore pile, the Taboshar "Hill".

Because the water in the area is in short supply, the water of the creek receiving the seepage from the low grade ore pile is indiscriminately used for watering of the animals that graze along the creek, for irrigation of rice paddies, irrigation of the gardens and orchards below the "hill".

Radiation exposure and uncontrolled spreading of contamination due to unauthorized digging and collection of non–ferrous metals from the old piles and mines presents a real concern in Taboshar and in all countries of Central Asia.

Prior to starting a remedial action the existing data should be complemented by specific measurements to be able to develop a conceptual plan of remediation. Simultaneously, a reliable monitoring program should be put in place to be able to control the performance of the remediation and to collect health and environmental data showing compliance with the required national/international standards.

Uzbekistan

From 1964 to 1995 uranium mining in Uzbekistan operated with conventional mining methods. The ore from the mines in the mountainous eastern part of the country, such as Yanghiabad (Tashkent district) and Charkesar in the Fergana Valley (Namangan district) was processed in the Leninabad Mining Chemical Industrial Combine (now State Enterprise «Vostokredmet», in Khujand, Republic of Tajikistan). The ore from the sandstone type uranium deposits in Central Kyzylkum (Navoi and Samarkand region) were processed at the Navoi Mining Chemical Industrial Combine in Uzbekistan (NMCC). Consequently, the only uranium tailings in Uzbekistan are at the NMCC site. With the introduction of In Situ Leaching (ISL) in 1995, all conventional uranium mines (open pit and underground) were closed down.

A legacy of the pre–1995 mining is piles of low-grade ore from the open pit mine in Uchquduq, which require safe containment. Important legacy sites in need of remediation are the former mine sites of Yanghiabad and Charkesar. The Jangiabad mine and the associated waste rock piles (approximately 500 000 m^3 extending over an area of 50 km^2) are located just above the town of Yanghiabad (Figure 4). The gamma dose rate in the contaminated area is 0.60 to 2.0 μSv/h and close to the mine access the dose rate is 1.4 to 2.5 μS/h. The gamma dose rate in the city of Yanghiabad is 0.2 to 0.4 μSv/h. The mine adit has not been plugged, thus allowing an uncontrolled drainage of the contaminated water from the mine, escape of radon exhalation and access for humans and animals into the mine. The uranium content of the mine water is up to 30 Bq/l; In addition, trace metals are present in the mine water. The mine drainage is discharging directly into the river water, which is used by the local population for drinking and irrigation purposes.

FIG.4. The uranium mining legacy site at Jangiabad. Mine adit and waste rock piles above the village.

To be able to assess the health and environmental risk of the legacy site it is proposed to establish a regular water sampling program of the river in Jangiabad and downstream before the river reaches the town Angren. Should it prove to be necessary, a simple entrapment of the mine water and a small water treatment facility could be installed at a relatively low cost. The possibility of construction of an engineered wetland for removal of uranium and of other toxic metals from the draining mine water should be investigated as well. The decision regarding the type of water treatment to be installed would depend on the chemical make up of the mine water.

The Charkesar legacy site is located on the foothills of the Kuraminskiy Mountain Range in the northwest part of the Fergana Valley, 20 km from the regional centre of Pap. The mine site is located on the slopes of a valley of a small mountain river across the village of Charkesar (population of 2500 people). There were 2 mines operated on the site - Charkesar-1 and Charkesar-2. The mining was by conventional methods and by underground leaching down to a depth of 280 m. After mine closure in 1995, most of the miners and professionals left the village because of lack of other work opportunities in the area.

The total volume of mine wastes left behind is 482 000 m^3, spread over an area of 20.6 ha. The piles of low grade ore and waste rock used to be partly covered by a soil layer but the cover has been badly eroded by rain. The gamma dose rate on the site is 3.0 to 4.5 μSv/h. The shaft of the underground mine has not been plugged and presents a safety hazard for the local population, which frequently visits the site. Mine water (about 3-5 litres per second) is seeping from the ventilation shaft located on a small hill. The mine water is contaminated and shows the visual characteristics of acid mine drainage, which is probably caused by remnants of the previous underground mine leaching. The ^{238}U activities in the drained water were measured by the IAEA experts to be in the range of 26–36 Bq l^{-1}. Beyond uranium, the mine water contains 5.2 Bq/kg of Pb^{214}, 4.0 Bq/kg of Bi^{214}, 2.7 Bq/kg of Ra^{226}. The soil in contact with the mine water contains 2.7 Bq/g of U and 62.8 Bq/g of Ra^{226}. After a short run, the untreated discharge from the mine enters the river bordering on the site.

However, the drinking water supply of the village (from a spring) does not show elevated uranium concentrations at all. More health relevant is that the drinking water has substantially elevated concentrations of heavy metals exceeding the safe levels.

The mine site is enclosed by a stone wall and warning signs posted on the wall indicate radioactivity (Figure 5). Nonetheless, the local population and cattle commonly access the site through the numerous places where the wall has been destroyed.

FIG. 5. The Charkesar-2 Mine area fenced off by a stone wall. The residential area is across the small river, which receives the discharging mine water.

Although the risk of having an unremediated site in the neighborhood of the village is not to be underestimated, of more immediate concern are the high indoor Rn levels in Charkesar. Systematic measurements within the NATO project carried out in public buildings constructed in which use of mine waste material was documented Rn concentration from 670 to 1410 Bq/m^3. In this regard it is of importance to extend the radon monitoring to the private homes which were constructed using mine waste material.

In view of these facts the most important first measures at Charkesar appear to be to: (a) make an accurate account of the mine waste inventory; (b) establish/improve a reliable monitoring program (including indoor measurements in the village; (c) remediate selectively the houses that are sources of high radiation dose and (d) improve the public education/information system regarding radiation protection.

The most significant legacy of the uranium processing in the past is the uranium tailings impoundments at Navoi, located 5 km from the Hydrometallurgical Plant No. 1 (HMP–1). Approximately 57M t (solid mass) of tailings having a specific activity of 10 to 110 kBq/kg produced during the uranium production period (1964 to 1995). The tailings were discharged into “flat” tailings impoundment structure (5 to 15m high) subdivided into 8 compartments. The total area of the impoundment is 637.1 ha. The dose rate measured 10cm above the uranium tailings surface is 0.5 to 1.7 μSv/h (500–1700 μR/h), the average radon exhalation from the tailings is 4.1 Bq/m^2sec.

Following the closure of the conventional uranium mines, HMP-1 has been refurbished for processing of gold ore (from the Muruntau Open Pit Mine). The residues of the gold processing are non radioactive gold tailings. Development of the remediation of the legacy uranium tailings under the new conditions led to the establishment of the “Project of ecological rehabilitation of tailings ponds of HMP-1 using gold processing wastes”. By systematically distributing the gold tailings discharge over the uranium tailings the required attenuation of the gamma radiation (to 1 μSv/h [100 μR/h]) and of the radon exhalation (to an effective dose of less than 1 mSv/a) is achieved and the deep percolation of the rain is prevented. In practical terms this could be achieved by building up the attenuation layer gradually by hydraulically spreading thin (15 to 20 cm thick) layers over the dried out tailings surface. A consolidation time of 15 to 20 days is usually required for each thin layer to acquire the necessary shear strength. The contraction cracks developing during drying are then filled in by the next layer. During the drying period the gold tailings discharge is directed into the next compartment. The required attenuation thickness is usually achieved by a 0.7 to 1.5 m thick gold tailings layer. The final surface - after gaining sufficient shear strength to carry machinery - is then capped by a 30 cm thick top soil layer, which can be vegetated, thus preventing wind erosion and dusting.

So far, more than 7 million tons of gold tailings have been used for covering of the old uranium tailings: Compartment No. 5 (100 ha) received a 1.5 m thick cover; Compartment No. 6 (80 ha) has a 3.5 m thick cover; Compartment No. 3 (110 ha) has 0.5 m cover. Currently (2008) the covering of the compartments No. 4, 7 and 8 is ongoing. It will take approximately 13 to 15 Mt of gold tailings to complete the construction of the attenuation layers and approximately 2 Mt of top soil to construct a cap in all compartments.

Although the hydraulic covering of uranium tailings with sand –taken from the less radioactive beach zones – is a common practice, it is usually employed to speed up consolidation. The procedure practiced at NMCC in Navoi provides a good example of making use of a commercially justified change of the hydrometallurgical process for the benefit of completing the remediation of a past legacy.

Kyrgyzstan Republic

The uranium industry in Kyrgyzstan history has many similarities with the other republics in Central Asia. The main uranium mining legacy sites are located at Mailuu-Suu, Shekaftar, Minkush, Kaidji-Say, Aktiuz, Kara Balta and others. According to an approximate assessment by the Ministry of Emergency, within the territory of Kyrgyzstan there are 35 tailing dumps and 25 sites where waste rock piles are situated. Among these, 30 tailing dumps contains the residue from uranium production from the past and also five storage facilities contain NORM residues derived from production of non-ferrous metals.

The Mailuu-Suu uranium deposit was exploited from 1946 to 1967. During more than twenty years of operation the Western Mining Chemical Combine in Mailuu-Suu (Figure 4) produced 10 000 t U_3O_8. There are 23 tailings dumps and 13 mine waste disposal areas on the site of the former enterprise, some of which are within the town boundaries. The total volume of tailings is approximately 1.4 to 2.0 millions m^3. The majority of the tailings dumps are located alongside the Mailuu-Suu River. After closure of production in 1966/67 the disposal into the tailings dumps ceased and the tailings sites were abandoned without remediation. Supervision and maintenance of the tailings areas was continued by staff of the industrial complex until 1991. The monitoring activities became sporadic after 1991.

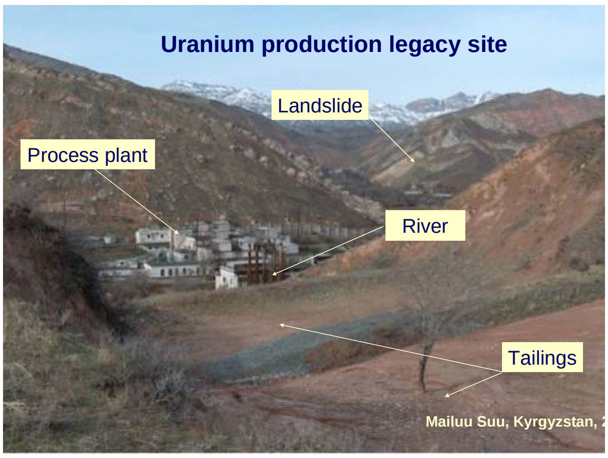

FIG. 6. The uranium mining and milling legacy site at Mailuu-Suu.

Concerning the urgency of remediation, the IAEA experts share the opinion of national and international experts that the first priority for a remedial action in Kyrgyzstan should be given to the Mailuu-Suu site. This is justified by the large volume of tailings on the site and the possibility of large scale landslides, possible flooding and ultimate structural failure, loss of containment and uncontrolled release of tailings from some of the impoundments. The overall hazard is heightened by the possibility of a seismic event.

The international visibility of the site has been raised by statements such as *"Mailuu-Suu is in the top ten of the most polluted places on the planet"* (Smithsonian Institute, Washington D.C., USA), which considerably affected the local public opinion. The less spectacular truth is that in spite of the publicity a radiation safety assessment of the site still has not been made.

The mean gamma-radiation exposure dose rates over the surface of the covered tailing piles are up to 1 µSv/h (from 60 to 100 µR/h). The background levels are typically 0.25 µSv/h (25 to 30 µR/h). At places where the cover was breached, high radon exhalation were detected, and the gamma-radiation exposure dose rate reached up to 15 µSv/h (1500 µR h^{-1}). The average annual gamma exposure dose rate was estimated to be 0.17–0.36 mSv/a. The annual dose rates "hot spots" can be up to 2–14mSv/a. For a number of tailings piles it can be expected that the exposure may exceed 1 mSv/a.

The spot measurements of ambient radon concentrations available from the Kyrgyz Ministry of Emergency indicate a large fluctuation from several hundreds to 1200 Bq/m^3. Indoor concentrations of radon of 10–1400Bq m^{-3} (with an average of 650 Bq m^{-3}) were measured in the town in buildings, located in the vicinity of the tailings piles.

The radioactivity of water and sediments in the river and in the drinking water was below safety limits. Recent measurements done at Chui Ecology Laboratory in Kara-Balta, indicate that the gross-alpha activities in river waters is less than 1 Bq l^{-1} in most samples. The existing data on the radioactive contamination of the river water is, however, very limited and does not provide a time dependent variation of the contamination. In spite of the sporadic data and lack of a proper radiological risk assessment it is safe to state that the radiological impact of the tailings landslide into the river (the worst case scenario) is very likely overestimated. Presently several internationally funded remediation projects are ongoing at Miluu-Suu from which the World Bank project funding the remedial works is the most prominent. One of the most significant achievements of the recent years is the mitigation of the potential landslide "Tektonic" and of several other landslide prone spots close to the tailing piles of Mailuu-Suu.

Another uranium milling legacy site is located in mountainous terrain in the broader area of the village of Min-Kush. The tailings are deposited in four impoundments at four sites: Tuyuk-Suu, Taldy-Bulak, "K" and "D". The mill operated from 1955 to 1960 and generated a total of 1.9 million m^3 tailings. While the tailings impoundments, Tuyuk-Suu (approx. 2 km from Min Kush); Taldy-Bulak (approx. 9 km from Min Kush) are located close to the river Tuyuk Suu, the tailings impoundments "D" and "K" are located in a high mountain bowl (approximately 11 km from Min Kush). The supervision and maintenance of the impoundments stopped 1991. Presently, the monitoring and maintenance of the impoundment is sporadic and here is no monitoring and maintenance of the other sites.

Although the Tuyuk-Suu and Taldy-Buluk impoundments on the river Tuyuk-Suu present a moderate risk for contamination of the river, which is flowing to the Fergana Valley and thus a remediation is justified, the condition of the tailings dams is stable and the implementation of a remedial action is not as urgent as of some other sites in Kyrgyzstan. What is, however, urgently needed, is the implementation of a monitoring and maintenance plan, particularly the regular cleaning of the by-pass canals at both tailings impoundments and the maintenance of the cover at Taldy-Buluk.

In a socially and ecologically sensitive situation on southern shore of the Lake Issyk-Kul is the relative small Kaji-Say mine/mill site. The facility was in operation from 1952 to 1966, using acid extraction procedures to obtain uranium from ash residue of brown coal mined locally. The coal was burnt in a heat and power generation plant providing the ash for uranium extraction. The tailings were deposited near the power plant and industrial complex on the mountain terraces approximately 2.5 km from Isyk-Kul, which is the receptor of primary concern. The volume of the accumulated uranium tailings and of other industrial wastes is approximately 150 000 m^3 and is spread over an area of approximately 1.1 ha. The pile was covered with a mixture of ash-clay, which proved to be inadequate. The face of the pile at the lower end was not covered.

After 1966, until 1991 the supervision and maintenance of the tailings was conducted by staff of the industrial complex. Presently, there are no regular inspections of the site, the access is not controlled and the site fencing is not maintained. The system of water diversion canals on the slopes above the pile has been destroyed. Approximately 2 km downstream of the tailings, the contamination movement in the ground water is observed in a drill hole but no ground water contamination has been reported so far.

In conjunction with the association of the uranium tailings with coal ashes the concern has been raised in 1995 that acid generation could occur in the pile. This can neither be confirmed nor disproved as there are no measurements of pH in the (rarely occurring) direct seepage from the pile. No visible signs (staining) could be observed during the IAEA mission to the site in 2007.

Because the tailings at Kadji-Say are from coal ash processing and the grain size very fine, larger amounts of the tailings can be transported by erosion over longer distances than tails from more coarsely milled ore. Severe erosion and displacement of the tailings kept on occurring since the construction of the pile and particularly after the maintenance work stopped. To prevent the contamination of the Lake Issyk-Kul the Ministry of Emergency ordered the construction of a protective dam below the main tailings pile in 1992. Prior to this, large quantities of tailings have already been displaced. In 2006, financed by ISTC, the tailing pile(s) received a cover that, however, was not completed and parts of tailings dump remained exposed. The cover was built as a multi-layer cover with the intent of reducing radon exhalation and gamma radiation as well as providing erosion protection and residue containment (Figure 7).

FIG. 7. The new containment dam (approximately 10 m high) and cover of the tailings (left) at the Kadji-Say facility built in 2005/6. The state of the new dam and cover damaged by water erosion in 2007 (right).

Although gamma radiation exposure presents a minor hazard–measurements on the tailings were up to 1.8–1.9 μSV/h (180 and 190 μR/h) (the background levels are at ~0.2 μSv/h (20–30 μR/h) covering of the waste would help attenuate both radon exhalation (measurements were not available) and gamma radiation. Due to the remote location of Kadji-Say the tailings pile does not present an immediate hazard for the local population. The persistent erosion of the tailings and the potential contamination of the Lake Issyk-Kul are the primary concerns at the site. The most important remedial actions would be the cleaning and repair of the existing run-off diversion channels, covering and re-vegetating of the pile surface and slopes and regular monitoring (including the ground water wells) and maintenance of the site.

A similar, independent assessment by the IAEA experts of the conditions at the legacy sites at Ak-Tuz and Kara-Balta would be highly desirable.

Kazakhstan

Among the Central Asian countries Kazakhstan has the strongest economy and a fast increasing uranium production. It is estimated that approximately 20% of the world uranium reserves are in Kazakhstan. The active uranium mining is the responsibility of the National joint stock company KAZATOMPROM.

According to a compilation made in 1993, there were 127 legacy sites left behind by uranium mining/milling of the past. Geographically, the legacy sites are located in three areas:

- ***Northern Kazakhstan*****:** 12 deposits; sites in the Kokshetau area Nr. 8, 9, 1, 3, 12, group of mines (Kosatchinnoe, Shatskoe, Glubinnoe, Agashskoe, Koksorskoe), Manybaiskoe, Stepnogorsk HM-Processing plant site with tailings; total amount of waste 81.2 Mt;
- ***Southern/central Kazakhstan*****:** 4 deposits; sites Kurdai, Vostochniy, Zapadniy, of the Zhanbyl region (South K.), Karasaiskiy, Ulken-Akzhal (Central K.); total amount of waste 117.8 Mt; and
- ***Western Kazakhstan*****:** 2 deposits; the Koshkar Ata site with tailings (near Aktau); total amount of waste 58.9 Mt.

The production in the listed mines was closed for economic reasons by middle of the 1990s. The inventory of the legacies approximately totaled: 368 Mm^3 mine waste piles; 13 Mm^3 low grade ore piles, 869 km^3 ore stockpiles, 4.9 Mt of metal scrap and building debris, a total of 865 ha of contaminated areas.

For remediation of the legacy sites an adequate legal framework was put in place and the Government of Kazakhstan established a State Program for “Remediation of (the sites left behind by) Uranium Mining Enterprises and Mitigation of the Consequences of Mining of the Uranium Deposits defined for the period 2001–2010”. The responsibility for implementation of the program was given to the Uranlikvidrudnik state enterprise, which was established in 2000.

The first remedial action included 6 sites in northern and two sites in southern Kazakhstan. The work followed the rules defined in the governmental decree “Sanitary Rules for Mitigation, Remediation and Interdepartmental Transfer of Installations for Mining and Processing of Radioactive Ores (SP LKP-98). Beyond radiation protection, the goals of remediation were to prevent: the contamination of the rivers; unauthorized access to the legacy sites; the use of mining waste as building materials and, dusting from the contaminated surfaces. An important difference from the point of remediation is that N. Kazakhstan is a moderately humid, prairie-like territory as opposed to central and s. Kazakhstan which is an arid, semi-desert. Some of the legacy sites are located in a mountainous area of s.Kazakhstan, such as the Kurday mine, Panfilov deposit and others.

By 2007 the closed out mines sites No. 12, 3, 1, Kossachinoye, 8, 9, 14 in N.Kazakhstan and parts of Vostochnyj (mining continues) and Kurdai were remediated. The remediation included:

(a) sealing and cementation of the shaft/raise openings;
(b) removal of the contaminated soil;

(c) collection of the scrap metal, disposal of the contaminated and recycling of the not contaminated scrap metal;
(d) decommissioning, dismantling, demolition and/or decontamination of related buildings and structures;
(e) disposal of the contaminated debris into waste piles,
(f) grading of the surface and concentration of the waste into rock and mixed waste rock/debris piles;
(g) covering of the piles with a soil cover up to 1 m thick; and
(h) fencing of the area if located within 5 km of a settlement (Figure 8).

In total, 43 shafts and 22 ventilation shafts and raises were decommissioned and plugged, approximately 75 Mm^3 of waste piles, 30 Mm^3 of mixed waste piles, 6.7 Mm^3 of low grade ore piles and approximately 400 ha of contaminated land have been remediated. Overall approximately 20% of the legacy sites had been remediated by end of 2007.

The problem of mine flooding and contaminated mine water drainage including the necessity of water treatment is to be addressed within the next phase of the remedial program. The stability of the walls of surface mines after flooding became a problem, which will have to be dealt with within the next phase of the program as well. Figure 9 shows an example of the collapsing walls of an open pit mine in northern Kazakhstan after ground water rebound.

FIG. 8. Covering the remediated slopes of the waste rock pile on the site of the mine No. 9 in N. Kazakhstan.

FIG. 9. Kamyshovoye deposit in n. Kazakhstan. Mine cave-in in the vicinity of the shaft No. 5 of the mine No. 3, mine administration No. 4.

The present (2008) remedial works are focusing on stabilization of the tailings at the Stepnogorsk site in northern Kazakhstan and the Koshkar-Ata site near the town of Aktau close to the Caspian Sea in western Kazakhstan. The completion of the work is expected by 2010.

An the site of the former Stepnogorsk Hydrometallurgical Plant, 46.8 Mt of the tailings were deposited in a tailings impoundment extending over 734 ha subdivided into three compartments. The present state of the compartments is as follows: compartment No. 1 is filled, compartment No. 2 is operational and receives tailings from the plant and compartment No. 3 is left to evaporate. Approximately, 1.5 Mt of tailings is discharged into the tailings impoundment annually. The tailings surface in all three compartments is dry but below the surface crust unconsolidated. The monitoring of the tailings impoundment does not indicate any contamination beyond the boundary of the sanitary zone. It is recommended to take up the monitoring of the tailings dust for alpha activity.

The operations of the Caspian Hydrometallurgical Plant left behind at Koskar-Ata approximately 52 Mt of mine waste spread over an area of 66 km^2 and uranium tailings covering an area of 77 km^2. The tailings were disposed in a natural depression close to the Caspian Sea but there is no danger of contamination of the Caspian Sea because the ground water level in the “tailings depression” is consistently lower than the sea level. Approximately half of the tailings surface area is covered by water, the other half is dry and a source of radon exhalation. The dry tailings are freely exposed to re-suspension by wind. The extent of the water cover varies with the seasons. The gamma-dose rates over the tailings vary from several Sv/h to approximately 10 µSv/h. The gamma dose rate measurements made by Uranliquidrudnik exceed at some places 10 µSv h^{-1} (1 mR h^{-1}). An area of over 15.8 km^2 in the southern part of the tailings pond was used as a dumping place for radioactive sources; Approximately 140 Kt of radioactive waste unrelated to the uranium processing operations were disposed here. The area of the tailings is commonly visited by the local population scavenging for scrap metal.

Beyond preventing access to the site and unauthorized collection of scrap metal, the main remediation goal is to prevent the dusting from the dry tailings beaches. Not far from the tailings pond is the scrap metal yard where the decommissioned equipment of the former Caspian Hydrometallurgical Plant was collected. The storage yard is surrounded by a concrete wall preventing access. However, a decision regarding the further fate of the scrap metal would be advisable.

The present remedial plans for the “Koshkar Ata” tailings deposit foresee the placement of a concrete cover over the southern parts of the tailings and covering by the waste rock from the adjacent pile. The planed remedial solution deviates considerably from accepted international practice of tailings remediation and it would beneficial for the country to subject the plans to an international peer review. An international review would be even more important for the plans concerning the complex remediation of the site.

CONCLUSIONS AND CONSTRAINS IN IMPLEMENTATION OF THE EFFECTIVE REMEDIAL ACTIONS

During the IAEA project almost all of the significant legacy sites of uranium mining and milling in Tajikistan, Kazakhstan, Kyrgyzstan and Uzbekistan were visited and received a first appraisal. Making due allowance for variation in climatic and geographic conditions, the technical legacy issues are similar to the problems encountered in other countries. The mine waste dumps, tailings impoundments/ponds and closed out mines were built many years ago and most of them incorporate outdated engineering technology. Impoundments and covers, if any, are susceptible to structural instability and destruction due to slope movement and slumping; landslides, extreme run-off and precipitation; severe water erosion of pile and tailings surfaces, containment structures and surface water diversion installations; wind erosion and seismic activity.

The most important constraints to the development of an efficient monitoring system and remediation plans can be summarized as follows:

- **Costs of remediation and limited availability of national funding.** In none of the Central Asian countries have any funds been set aside for mine closure and remediation. Except for Kazakhstan, none of these countries has a systematic national program for remediation of the legacy sites. Considering that the GNPs in Uzbekistan and particularly in Kyrgyzstan and Tajikistan are considerably lower than in Kazakhstan, it is considerably more difficult for these governments to dedicate adequate funds for this purpose without an incentive. The case of Kyrgyzstan demonstrates that a combined national/international financing program would be a feasible approach to this problem.
- **Inadequate institutional framework for mine closure and environmental remediation.** In most of these countries since national independence no adequate institutional infrastructure has been in place to protect the population. Since the departure of the Soviet Union, inspection, monitoring and maintenance programs have essentially been discontinued. This is of significant concern, given that the structural and environmental integrity at the sites is highly dependent on maintenance of the containment works and functionality of the surface water diversion installations. The requirement to assess, monitor and, if justified, remediate the legacy sites must come from a consistent set of legal health and environmental protection requirements and from the mining law. A set of legal acts, decrees and regulations, which rule the remediation are in place and are being applied in Kazakhstan. An understanding of the complexity of the remediation issues, prompted by the case of Mailuu-Suu, is developing in Kyrgyzstan. The national regulations should conform to the international standards of the IAEA and other relevant international institutions (ICRP etc.) and be consistent with other jurisdictions that have experience in this area.

The relevant institutions should be strengthened by developing and providing:

- a clear mandate and responsibility;
- specific Terms of Reference to guide their management;
- adequate staffing, equipment and funding;
- coordination strategy re cooperation with other relevant institutions;
- training of the managers and key technical staff; and
- public consultation mechanisms and stakeholder policy.

- **Inadequate knowledge of the inventory of the legacy components and the risks associated with them.** Except for some obvious cases, such as Mailuu-Suu and similar sites, there is presently no sufficient reliable data for assessment of the "realistic" risks presented by the legacy sites. The development of remedial plans, maintenance and monitoring of the sites must be focused and carefully managed in order to be technically sound and cost effective.

URANIUM MINING AND MILLING ENVIRONMENTAL LIABILITIES MANAGEMENT IN AUSTRALIA

P. W. Waggitt
Office of the Supervising Scientist-Environment Australia, Darwin, Australia

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Abstract

Uranium mining has been conducted in Australia since the 1920s. The standards of environmental management and remediation at many of the older mines were not high and often left a legacy of environmental degradation and ongoing impacts. Since the 1970s, environmental management and remediation have been considered more seriously. Changes in legislation and increasing community expectations have resulted in improved management performance and better remediation outcomes. Some former mines have had improved remediation carried out progressively and other abandoned mines are currently the subject of active remediation programmes. Both types of activity are briefly described. Also, planning for remediation is now required by the regulating authorities and the paper reviews the current situation at each of the three operational uranium mines in Australia and two anticipated projects. Progress on two current remediation projects is described. In the South Alligator valley, 13 small mines from the 1960s are being remediated after earlier having been abandoned and at Nabarlek, the remediation programme is in its final stages. Finally the paper discusses briefly the issues of long term management and stewardship for all uranium mines once they have ceased operating.

INTRODUCTION

The mining of uranium has been taking place in Australia since the 1920s, but only in earnest since the 1950s and has been well documented elsewhere [1]. This paper sets out the present situation in terms of the remediation liabilities and planning arrangements for the current operations and projects-in-waiting. The three operational mines are at Ranger (an open pit mine), Olympic Dam (an underground facility with a mixed ore body of copper, gold and uranium) and Beverley (an in situ leach project). In addition there is the underground project proposed for Jabiluka which is currently on care and maintenance, as is the in situ leach project at Honeymoon. The locations of the projects are shown in Figure 1.

The paper also briefly deals with former uranium mining operations which are currently being remediated and managed. These include mines abandoned around 1964, when there was no environmental protection legislation eg the South Alligator valley area [2]; the former Rum Jungle minesite, where there are issues of the sustainability of the remediation which was completed in 1986 [3]; and the more recent Nabarlek mine where remediation work is in the final stages [4, 5].

The paper does not discuss the issues of long term monitoring or stewardship in detail, these very important issues are being discussed by the various stakeholders and some preliminary planning has taken place [6]. The liabilities in terms of resources and responsibilities for these essential tasks have yet to be finalised in most cases. However they will be referred to again later.

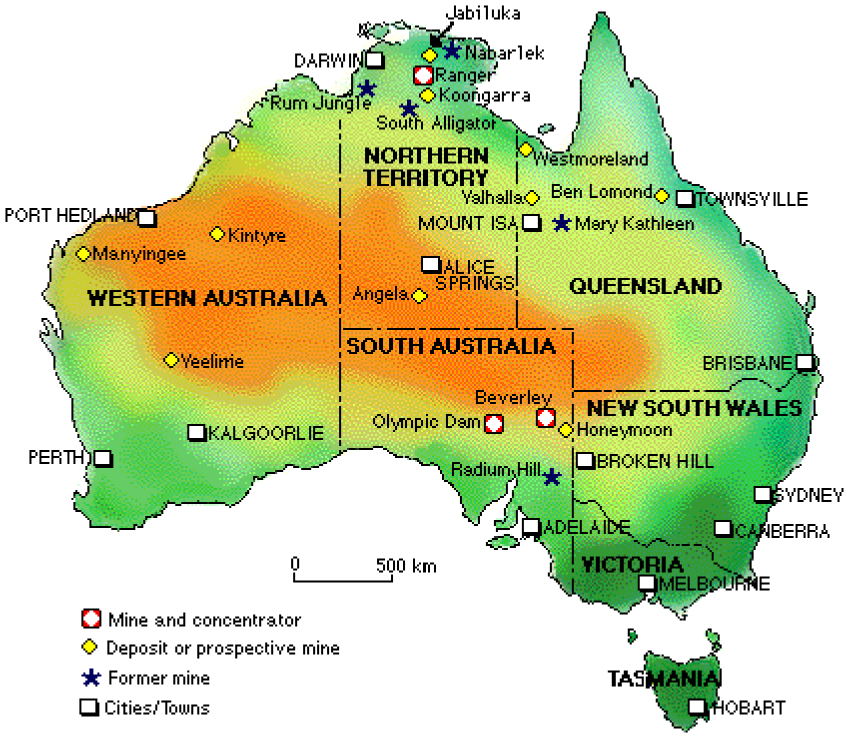

FIG.1. Uranium mining activities in Australia (courtesy of the Uranium Information Centre).

THE ACTIVE MINES

As mentioned previously, there are currently three active uranium mining operations in Australia. A fourth is due to start up in 2008. The following sections briefly describe the operations in turn followed by the details of their respective remediation liabilities. The information provided in this section is based on the data provided in an OECD/IAEA report [7].

Ranger uranium mine

Located about 250 km to the east of Darwin in the Northern Territory, Ranger is owned and operated by Energy Resources of Australia (ERA), a part of the Rio Tinto Group. The resource was discovered in 1969 and was estimated at 124.63 1t U_3O_8 located in two ore bodies [8]. The mine began operations in 1981 from orebody #1 which was exhausted in 1995. Since 1997 mining has been from orebody #3 and this is expected to continue until about 2010 with milling of stockpiles to go until 2015 possibly. The estimated total reserves in December 2006 (stockpiles and in situ) were 50.689 t U_3O_8 [9]. Mining is by conventional open pit methods and current production rate is about 5400 t/a U_3O_8 with a maximum installed capacity of 6000 t/a. The operation is located on a project area of 7860 ha owned by Aboriginal Traditional Owners and is surrounded by the World Heritage listed Kakadu National Park. The operation is closely regulated and environmental protection is required to be of a high standard [10]. To date about 500 ha have been disturbed by the mining and milling operations. The milling process utilizes a sulphuric acid leach with pyrolusite as the oxidising agent. Recovery of uranium from solution is by a solvent extraction process using an amine dissolved in kerosene, followed by precipitation using ammonia and calcining of the precipitate to produce U_3O_8.

The remediation plan for the site has been in existence since the Environmental Impact Statement was completed in 1978 and is updated every year. The current plan is finalised in April each year after review by the Northern Territory regulating authorities, the Commonwealth Government's oversight agency, the Supervising Scientist Division, and the Northern Land Council, acting as representatives of the Aboriginal Traditional Owners. Before the agreed plan is finally accepted by the appropriate Federal Minister, ERA is required to deposit cash, or similarly acceptable financial instruments, in a remediation trust fund. The amount of the bond is set after costing of the approved plan by an independent assessor acting on behalf of the Minister.

As part of its original approved plan, ERA was required to deposit all tailings underground in the mined-out pits and for all the tailings to be finally contained below present day sea level. At present, active tailings deposition is into the former #1 pit and the level of tailings is allowed to rise a few metres above sea level but still well below the rim of the pit. The old tailings dam still contains about 13.1 M cubic metres of tailings that will need to be transferred to the mined-out pits at decommissioning. The process water circuit holds about 10 ML of water that will require evaporation and/or treatment before decommissioning is complete, a further 2.3 ML of less contaminated water will also need to be irrigated or treated by the end of decommissioning. ERA has installed a treatment system for contaminated water which is operated in conjunction with a series of constructed wet-land filters. The treatment of process water may also be under consideration as a series of wetter than average years - 2006 and 2007 -has recently increased the volumes of all classes of water in storage at the site with some adverse impact on operations

In terms of waste rock, most is due to be relocated to provide covers over the tailings in the pits and the low level mineralised materials. Also there will be aesthetic reshaping of stockpiles to create an acceptable landform. It has been estimated that up to 32 M cubic metres of rock may have to be moved. The overall cost of these operations was estimated at A$35.2 M in April 2002. The original deed of agreement for the project required remediation to be completed within 5 years of the cessation of mining but it has recently been accepted that remediation may take up to seven years, after which there will be a period of monitoring before issuing of a revegetation certificate by the regulating authorities. This certificate will acknowledge that ERA is no longer liable for activity at the site. Monitoring and stewardship are likely to continue at the site, but the final details have yet to be agreed between the main stakeholders and the Aboriginal Traditional Owners.

Olympic Dam uranium mine

The Olympic Dam facility is located at Roxby Downs in South Australia, about 450 km northwest of Adelaide. The mine is operated by Olympic Dam Operations, a part of the Western Mining Corporation. The deposit was discovered in 1975 [11]. The facility has proven reserves of 73 800 t U_3O_8 within a complex orebody dominated by copper and uranium with significant amounts of gold and silver. There is an estimated mineable reserve of 717 Mt of ore containing 1.7% copper, 0.5 kg/t U_3O_8, 0.6 g/t gold and 4.9 g/t silver. Construction began in 1985 within a project area of some 12 000 ha although the actual disturbed area is about 600ha. Uranium mining commenced in 1985 and milling began in 1988. The production capacity is around 4300 t/a U_3O_8. The process is conventional acid leach with solvent exchange to recover the uranium. Tailings are managed by using the coarse fraction, about 20%, in conjunction with waste rock and specially quarried materials as underground backfill in old workings. There is no significant waste rock stockpile at the surface at this mine. The fine tailings material is pumped to above ground paddocks, contained by ring dykes, which cover an area of about 395 ha. In 2003 about 46 Mt of tailings were contained in this way with a production of about 8.6 Mt being added annually. There is also a 30 ha pond for the disposal of excess mine water and 110 ha of lagoons in 4 ponds used for the evaporation of tailings liquor. The final remediation solution is for in situ covering of the tailings paddocks.

The remediation plan has been drawn up and is reviewed and re-costed annually. Each year money is placed in the remediation fund which currently stands at A$14 M. The 2003 estimate of the remediation costs was A$130 M of which the remediation of the tailings had been estimated to cost A$65 M. Although the remediation plan does exist, the operator has committed to using best practice at the time of the final decommissioning. The current estimate of mine life is about 60 years. However, expansion plans are under investigation which would greatly alter the situation, if they are fully implemented. The issues of long term monitoring and stewardship have been discussed with the regulating authorities from the South Australian Government but final decisions will be made nearer the time of decommissioning.

Beverley uranium project

The Beverley uranium project is located about 530 km north of Adelaide in South Australia. The resource was discovered in 1969 and contains about 21 000 t U_3O_8 deposited in the sands and clays of an isolated aquifer located between 100 and 140 m below ground in three main lenses [11]. The original discoverers of the deposit sold it on when development was hindered by the policy of the government of the day. In 1990 the site was acquired by Heathgate Resources Pty Ltd, a part of the American General Atomics Group. The extraction process is by use of the in situ leach process (ISL). The total project area extends over 13.50 ha. The current operational mine site covers about 500 ha but only about 50 ha are required for the active well field at any one time; there is no open cut nor any constructed underground workings. The associated infrastructure includes a gas-fired power station, the processing plant, a small camp for workers and an airstrip.

The extracting solution is weak sulphuric acid with oxygen or hydrogen peroxide as the oxidising agent. The solutions are pumped underground to dissolve the uranium and then recirculated through an exchange process where the uranium is stripped from solution using an exchange resin. The uranium is stripped from the resin into solution and precipitated using hydrogen peroxide, dewatered and dried to obtain the final product, uranium peroxide ($UO_4.2H_2O$). Production mining commenced in 2000, although no product was shipped until 2001. In the first production period 2000/01 219 t of product were shipped, 2006–2007 production was about 850 t. The facility is licensed to produce 1180 t/a of U_3O_8 equivalent.

As the operation depletes an area of the orebody the well field is decommissioned, wells are sealed and capped, and the pipework relocated to the next area to be exploited. The ground surface is barely disturbed as there are no significant earth moving activities associated with ISL mining. However, vegetation is assisted to re-establish itself where necessary. The area surrounding the deposits was formerly a pastoral property which was de-stocked when it was acquired by the mining company. The mining company is obliged under the legislation to leave the site in a state compatible with the final land use agreed to with the stakeholders and Traditional Owners of the area. This will include the treatment of wells, as described previously, and the dismantling and removal of all unwanted infrastructure, such as the processing plant and evaporation pond. This last feature is relatively small with dimensions 130 m x 100 m approximately. The company is required to monitor soils, water and air in accordance with a program set out in the Environmental Monitoring and Management Plan, the Radiological Management Plan and the Radiological Waste Management Plan. These plans are approved by the regulating authorities. Reporting to the authorities is carried out quarterly and annually. The cost of decommissioning and remediation of the Beverley minesite is assessed annually and the amount is kept in bond by the South Australian Government. The exact sum held at present has not been publicly disclosed.

New and future mines

There are number of potential uranium mining projects throughout Australia. The degree of development ranges from imminent implementation to little more than an identified resource. In 2003 only two had been developed to the extent that significant remediation would be required should development stop. Since then the Honeymoon project has been given the “go-ahead” by the South Australian Government in 2008 and the Jabiluka project has been placed in long term care and maintenance after remediation work was carried out at the site in 2003.

Honeymoon

The Honeymoon deposit is another ISL site which was discovered in 1972. The site is located 75 km northwest of Broken Hill, but is actually located within South Australia as are the Olympic Dam and Beverley operations. The deposit is currently owned and operated by Southern Cross Resources, a Canadian company, and has been estimated to contain at least 6800 t U_3O_8. The deposit is located in sands at depths of between 100 and 120 metres and extends over an area of about 150 ha. A pilot plant was established in 1981 but abandoned in 1983 when it was apparent that development approval would not be forthcoming. The field trails were recommenced in 1998 after the trial plant had been refurbished. The project is currently on a standby basis pending final development details and the outcomes of further exploration on surrounding properties. An acid leach system for the ISL has been proposed with initial production of U_3O_8 equivalent anticipated to be about 500 t/a, rising to about 1,000 t/a at full development. As for all ISL projects, the level of environmental disturbance above ground will be minimal with an extensive pipeline network and the process buildings being the only above ground facilities. The details of the remediation plan are not publicly available, neither is the estimated cost of remediation. The approval to commence operations was granted in January 2008.

Jabiluka

The Jabiluka deposit is located some 25 km to the north of the existing Ranger mine in the Northern Territory. The deposit has been owned by ERA, the operator of Ranger, since 1991 when it purchased the lease from Pancontinental Mining Limited who discovered the deposit in 1971. Development of the site was prevented by Labour Party policy until 1997 when a change of government allowed the mining company to seek permission to develop the site. A new EIS was commissioned in which the resource was estimated at 71 000 t U_3O_8 [12]. A proposal was accepted for the construction of facilities that would be common to the two development options proposed; both were for an underground mine but the milling was either to be on site or at the existing Ranger mill, which was ERA’s preferred option. In 1997 ERA submitted a revised proposal for a mill on site with the tailings to be placed underground either as backfill in the stopes or in specially constructed chambers in the sandstone overlying the host rock for the orebody. This was approved by the Commonwealth (Federal) Government, subject to agreement by the Aboriginal Traditional Owners which has not yet been forthcoming.

Initial site development commenced and approximately 2000 m of underground passages were constructed including an access decline of about 1100 m and drives across the ore body and along the footwall. At the surface, there was a clean waste stockpile, a workshop and fuel storage facility, an interim water management pond with an area of approximately 3.5 ha, and a mineralised material stockpile containing about 40 000 t of material, all of which was been stacked under a waterproof cover.

After a short period of underground investigative work ERA placed the site on a care and maintenance basis whilst continuing to negotiate issues of road construction and access in relation to the option for milling at Ranger with the Aboriginal Traditional Owners. ERA has agreed that the mine would not be developed and operated simultaneously with the Ranger operation.

As a condition of the original Authorization to Operate issued by the regulating authorities ERA was required to prepare a plan of remediation and update it annually. In 2003 ERA agreed to place the site in long term care and maintenance until a final agreement with the Traditional Owners on the mine's development had been reached. The remediation works carried out included removal of all mineralised material to the underground workings, backfilling of the decline, treatment of contaminated waters to enable them to be discharged to the surrounding environment (which includes the World Heritage listed Kakadu National Park), removal of infrastructure and final landscaping and revegetation.

Other projects

There are a number of other potential uranium mine projects in Australia but none are considered to be close to development and remediation requirements are minor by comparison with the sites mentioned previously. With the upsurge in uranium prices since 2004 exploration activity has restarted at many of these deposits. Details may be found on the website of the Uranium Information Centre (www.uic.com.au).

CURRENT REMEDIATION WORKS

Remediation is currently underway at two former uranium mining locations in the Northern Territory, the South Alligator Valley mine field and Nabarlek mine site. A literature and website search has not found any other active remediation works in relation to uranium mining in Australia. There are several uranium prospects where some disturbance of the environment occurred but none of them was actually a mine. Former minesites now remediated include Rum Jungle, Radium Hill and Mary Kathleen.

South Alligator Valley

The uranium mines of the South Alligator Valley in the Northern Territory were exploited from about 1955 to 1965. The sites were then abandoned, as there was no environmental legislation requiring operators to rehabilitate sites when they were relinquished. In the early 1990s, the Commonwealth Government undertook some hazard reduction works to reduce the risks to tourists who were entering the area in increasing numbers following the gazettement of Stage 3 of Kakadu National Park and its subsequent listing on the World Heritage register. The land was also subject to a claim under the Land Rights legislation which was granted in 1996. This meant that land ownership was returned to the Aboriginal Traditional Owners who immediately leased the area back so it would remain as a national park. The lease required that all former minesites be remediated. The full story of these events has been reported elsewhere [2, 13]. At present a team of consultants and specialists from various government departments is working on a plan of remediation for the sites in the valley. Eighty per cent of the sites have no serious radiological issues associated with them and so remediation plans have been agreed in principle with the Traditional

Owners [2]. The overall cost of the operation was initially calculated to be in the range A$5-A$10 M depending on the choice of options selected for the management of the radiologically contaminated sites. In 2006 the Commonwealth Government set aside $7.5 million which was the final estimated cost of the programme. Most of the works will be earthmoving to provide stable landforms that can be revegetated to blend in with the surrounding countryside to the maximum extent practicable. The first two sites were completed in 2007 and work will continue in 2008 with completion anticipated in 2009. Under the terms of the lease the remediation work all has to be completed by 2015.

Nabarlek

The Nabarlek uranium mine operated from 1978 until 1988, at which time the mill was mothballed. In 1994 the mining company was directed by the regulatory authority to decommission the mill and rehabilitate the site. This process has been described in some detail elsewhere [5].

The earthworks were completed in December 1995 and the site was seeded for revegetation. The establishment of the appropriate mix of native trees, shrubs and grasses has proven to be more difficult than originally anticipated. After initial apparent successes the plant population has not established uniformly across the site in the manner desired by the Traditional Owners and the Supervising Authorities. The problems of establishing a successful remediation have been reported in depth elsewhere [14]. The cost of the original remediation was estimated at A$10 M, and the mine's operator was required to provide a company financial guarantee for that sum throughout the works period.

The mining company has not yet been released from it's obligation as the regulating authority does not consider that it is appropriate to issue a revegetation certificate until such time as the various stakeholders are all agreed that the site is developing an appropriate, self-sustaining ecosystem that blends in with the surrounding countryside. The mining company has spent considerable sums of money in recent years on various works associated with the ongoing need to establish successful revegetation of the site. These have included some planting and reseeding programs, establishment of a plant nursery in a local town and employment of Aboriginal Traditional Owners to work on grass clearing and tree planting projects. A cyclone in 2006 devastated the vegetation on the site and in the surrounding district. Work has resumed since then to keep the revegetation programme going. There is also an ongoing issue of final clearance of the remnant infrastructure, especially in the former accommodation camp area. Semi-dismantled buildings, fuel and water storage tanks, electricity wires, drain pipes and concrete building bases all remain to be cleared. These represent the remains of assets transferred to the Aboriginal Traditional Owners and then sold to contractors who failed to clear the site properly.

The size of the outstanding liability has been estimated at up to A$250 000 for the infrastructure works and outstanding revegetation proposals. At this time there is no indication of when the liability for the site will be discharged. Also a research program was carried out, under the auspices of the Australian Centre for Minesite Environmental Research, to determine the most appropriate way to assess the success of revegetation and to establish an end point which will enable release of the site from regulatory control. At present environmental monitoring is carried out by the regulating authority in respect of surface and ground waters whilst the mining company is responsible for providing suitable photographic records of the progress of revegetation. The final plan for long term monitoring and surveillance of the site has yet to be agreed but discussions between the various stakeholder organizations are on-going.

Rum Jungle

The uranium resource at the Rum Jungle mine was exploited from 1949 until 1958 and copper mining continued until 1965, the mine finally closing in 1971. The uranium was mined on behalf of the Commonwealth Government who, at that time, had no legal obligation to rehabilitate the site, which was simply abandoned. Buildings and machinery remained on site decaying; tailings frequently washed away into the Finniss River; and sulphides in the stockpiles weathered to sulphuric acid leading to releases of substantial amounts of metals and other pollutants into the Finniss River. A clean-up operation in 1977–1978 was not wholly successful, achieving some revegetation, but completely ignoring the issue of acid rock drainage and the associated pollution from the waste stockpiles [15].

In 1980 the Finniss River was by then virtually devoid of aquatic life for about 14 km downstream of the site. Growing public concern about these impacts resulted in the Commonwealth Government agreeing to fund a remediation program which was undertaken on it's behalf by the Northern Territory Government. The program ran from 1982 until 1986 at a cost of A$18.6 M [16].

The major objectives of the program [15] were to:

- reduce the pollutants leaving the site by specific amounts (Cu by 70%, Zn by 70% and Mn by 56%);
- restrict water infiltration in waste rock piles to 5% of incident rainfall;
- contain and reduce pollution in the water-filled open cuts;
- reduce radiation levels to suitable levels; and
- make the area safe and to improve the site's visual appearance.

Finally, it was required that the works had a structural life of 100 years. There was no intention that the site should be remediated so that the public could have unrestricted access. In the works program, tailings were contained, waste rock was encapsulated in new landforms to restrict the ingress of air and water, wastewaters were treated to raise pH and remove heavy metals, and the site was revegetated. The grass species used were non-indigenous and needed fertilising and mowing to maintain the effectiveness of the cover. The result was a site quarantined from any future use and which required ongoing management for the remediation to remain effective. Such outcomes would be unacceptable today.

Whilst such an outcome was apparently acceptable in the 1980s, modern communities expect former minesites to be restored to a productive use. This became apparent when the outlying mine at Rum Jungle Creek South was remediated in 1990–1991. The program there required the former open cut, waste rock dump and surrounding area be remediated to become a recreational lake and picnic area with unrestricted public access [17].

A further issue is the sustainability of the remediation. At the main Rum Jungle site it has become apparent in recent years that the covers on the waste rock dumps are no longer performing to specification [3]. The long term prognosis cannot be good and it is possible that the increased rate of rain infiltration into the heaps of reactive rock will result in increasing levels of heavy metals, especially copper, being leached into the environment, not least into the Finniss River. At present, the re-characterization of the site has been undertaken as a new mining project has been proposed for part of the area; such a development could have significant environmental consequences if it were to involve relocation or other disturbance of all or part of the waste rock dumps.

LONG TERM ISSUES

The long term management of all former mine sites once they have been "certified' as remediated is a topic that is becoming more significant as more mines approach the end of their economic lives. For uranium mines the issues are perhaps more pressing as the spectre of radioactivity looms large in the public's mind. The general consensus amongst the regulating and supervising authorities is that there is no such option as "walk away" and that some form of monitoring and surveillance program will be required at all uranium mining and milling sites for a very long time in order to meet the community's expectations. This was one of the significant conclusions reached at a multilateral exchange meeting held in Vancouver in 1997 [18]. Also the local community must be involved and have ownership of the long term management of such sites, the concept of stewardship. There are several models for stewardship but none has yet been fully implemented nor proved successful, although many have come close and may yet succeed. The US Department of Energy previously had a regular workshop on the topic which alternated between venues in Grand Junction and Denver, both places being in the State of Colorado [19].

In Australia the situation is similar with much discussion taking place in several jurisdictions but few firm conclusions being reached. The major elements of stewardship seem to include long term environmental monitoring, frequent communication with, and involvement of, stakeholders, especially local communities and traditional landowners, and transparency of process at all stages. Certainly the long term sustainable and productive use of former minesites is a very important issue and one which will continue to receive significant attention from regulators, politicians and the stakeholders.

SUMMARY AND CONCLUSIONS

The outstanding environmental liability arising from uranium mining in Australia is significant. However, for the most part, processes and institutional arrangements are in place to address the issue of liabilities, long term remediation and management and, most importantly, the cost of remediation.. There should be no recurrence of the past history of abandoned sites where contamination has spread downstream and where there are still problems of reactive waste rocks and excessive erosion. Regulatory authorities now require remediation planning to be incorporated in operational plans right from the start, even in the environmental impact stage prior to development. The resources to be allocated must be adequate not only physically but also financially, and suitably guaranteed so that society as a whole is not required to bear the cost of clearing up after industry any more.

Within the Australian uranium mining industry the issue of future environmental liabilities is being well managed. Although there are significant variations in institutional requirements between jurisdictions in terms of the backing for financial guarantees, in all cases some form of guarantee does exist for operating and possible future mines ("mines-in-waiting"). The total of environmental liabilities for these operations is substantial, but then so are the processes and procedures put in place to manage them.

The only issue is in respect of mines where remediation was completed some time ago and the operating company has been released from any further obligation in terms of environmental management. Best practice remediation is a continuously developing science and the knowledge gained from the past 20 years has led to some significant changes in dealing with final voids, waste rocks, acid rock drainage, tailings, waste waters, etc. Hopefully the operators, regulators and stakeholders of today are sufficiently well aware of these issues that arrangements are in place to deal with the possible contingencies that could arise.

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REMEDIATION OF THE URANIUM PRODUCTION SITE OF POCOS DE CALDAS

M. R. Franklin[1,] *H. M. Fernandes*[2]
[1] Institute of Radiation Protection and Dosimetry, Brazilian Nuclear Energy Commission
[2] IAEA, Vienna, Austria

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Abstract

This paper describes the challenges related to the closure and environmental remediation of the first uranium mining site in Brazil. It is demonstrated that under the technical point of view the main issue to be dealt with is the abatement of the acid drainage generation from the existing waste-rock piles and tailings dam as it has been estimated that this phenomenon will last beyond 500 years. It has also been discussed the necessary administrative arrangements that will need to be put in place as to involve the operator, regulators and other relevant stakeholders throughout the process, i.e. from the beginning of the planning phase. The regulatory environment in which these activities will have to take place is described and attention is called to the fact that the country does not possess specific regulatory requirements for the closure and environmental remediation of uranium mining sites. Finally it is suggested that the operator may and should find the support of international organisms like the International Atomic Energy Agency to improve its capabilities to face these challenges in the most effective way.

INITIAL CONSIDERATIONS

The uranium industry in some countries is developed to provide fuel for its own nuclear program. For some strategic reason[†] the country may wish not to rely on the supply from external sources and the self reliance on nuclear fuel may imply in the development of mining projects that would not be normally developed if market based considerations were taken into account. For example, the country may wish to develop production centers that process low grade ores and by doing so, large waste disposal areas (including large dumps or tailing dams) may be originated or multiple mining sites may be created.

Historically, these decisions have been made with little or even no consideration at all of future environmental remediation (clean-up) costs. As a result, when the ore deposit is exhausted and mining and milling operations need to be terminated, operators (generally state owned companies) have to face large remediation costs that will eventually not be able to be afforded. It is also observed that in some countries the necessary expenditures with environmental remediation programs will have to compete with other social needs and remediation projects will suffer delays in their implementation (if implemented at all). Nevertheless, post-operational costs will have to be faced – eventually for a long time – as for example treatment of acidic waters generated by the oxidation of sulfidic material in waste-rock piles.

The lack of experience in decommissioning/remediation programs is another important issue to be faced as site-release from regulatory or institutional control is only a mature practice in those countries that have completed a certain number of decommissioning/remediation

[†] The Brazilian economy grew 7.4% per year on average between 1950 and 1980. This growth slowed in the 1980s to some 1.6%. There were a number of reasons for this one of them was the dramatic increase in world oil prices. Brazil was then forced to reduce oil imports and the Government encouraged the replacement of primary fuels. The Brazilian Nuclear Program was part of this strategy

projects. These are generally more affluent countries like Germany, USA and France that have invested hundreds of millions of dollars in environmental remediation programs of former uranium productions centers. An important point is that experience gained in the decommissioning/remediation of sites in developed countries may not be readily transferred to developing countries due to innumerous specific conditions.

Ideally, remediation plans must demonstrate how it will be assured that the site complies with (existing) release criteria. It must comprise the identification of the radiological contaminants, the classification of the impacted areas, the methods and performance criteria used. Release of the site, after remediation, is based on demonstration that no residual radioactivity above release levels is present on the site.

This can be achieved by:

- carrying out measurements on the site(s) to be released; and
- systematic and careful evaluation of the operating history and thus the contamination history of the site and by demonstrating that no contamination could have been deposited on the part of the site to be released.

Independently of the availability of resources to carry on environmental remediation works, these operations must be well designed in order to maximize their benefits and reduce costs. In order to achieve these objectives, good and solid understanding of the basic processes in charge of the mobilization of contaminants and exposure pathways to radiation from different sources must be achieved leading to a perfect integration of safety requirements and remediation technologies. The operations must be linked in a logical way and understood and accepted by the different stakeholders. As long as these concepts seem to be logical in nature, they are not easy to be implemented.

The objective of this text is to describe the environmental remediation challenges concerning the first uranium mining and processing facility in Brazil which ceased production operations in 1997. It will describe the works already developed to support the decision making process of the regulatory authority in terms of the proposals to be formulated by the operator and point out to urgent need to formulate a general strategy to face this challenge.

DESCRIPTION OF THE URANIUM MINING AND MILLING SITE OF POCOS DE CALDAS

The Poços de Caldas mining site is located in the Minas Gerais state, in the southern region of Brazil (21^o 45' S latitude and 46^o 35' W longitude). The alkaline complex corresponds to a circular volcanic structure whose formation began in the upper Cretaceous (87 ma) and evolved in successive steps until 60 ma (Figure 1). This intrusion is rounded by the levelling of bed rocks, consisting of granites and gneisses. These rocks are frequently cut by diabase dykes, amphibolites and gneisses.

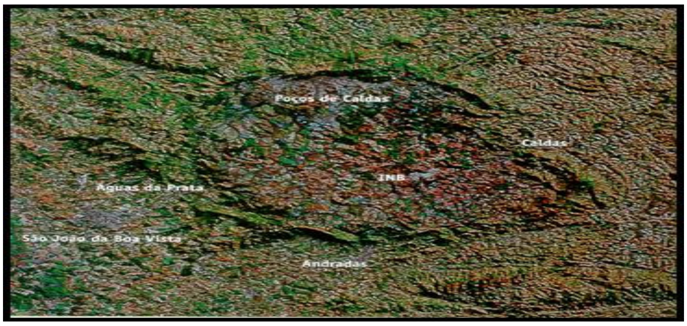

FIG. 1. Poços de Caldas Volcanic Crater (Landsat Satellite Image).

These igneous-policyclic activities of alkaline nature, associated to intense metassomatic processes and a strong weathering, gave rise to a variety of rock types belonging to the Nepheline-Syenite family and to uranium mineralization. The uranium enrichment in Poços de Caldas mine is related to hydrothermal events (primary mineralization) and to latter weathering processes (secondary mineralization). The mine covers an area of about 2.5 km^2 and has been divided into three mineralised units designated as ore bodies A, B and E for mining purposes.

The mining and milling facilities began commercial operation in 1982. However, the original intended production of 500 t of U_3O_8 per year was never reached. The uranium deposit is defined as being of low grade associated with a primary mineralization of Zr-RE-U-Th-Mo (bodies A and B) and a secondary mineralization caused by hydrothermal processes (body E). Uranium occurs in the form of pitchblende, although brannerite ($UTiO_6$) was also identified in marginal proportions [1]. The rocks are known as potassic rocks with varying proportions of mafic and nefeline syenite minerals. As of 1995, 1172 t of U_3O_8 were produced. This amount corresponds to a uranium concentration in the range of 675–1700 mg.kg^{-1}. In the development of the mine 44.8 x 10^{6}m^3 of rock were removed. From this amount, 10 million t were used as building material (roads, ponds, etc). The rest was disposed into rock piles, the two major ones being waste rock pile 8 (WRP-8) and 4 (WRP-4). Presently acid waters are being collected and pumped to the neutralisation unit. Chemical treatment consists of the addition of $CaCO_3$ and CaO. The overflow is released into local river waters and the solid treatment sludge (precipitate from the neutralisation process) used to be disposed of in the tailings dam but now is disposed of the mine pite (Figure 2).

The milling process consisted of the addition of an oxidant (pyrolusite) to the ore and subsequent sulphuric acid leaching. Then the uranium used to be extracted from the liquid solution with an organic solvent and precipitated with NH_4OH. The chemical processing produced large quantities of liquid and solid wastes, which were neutralised by $CaCO_3$ and CaO to pH 9 and then discharged into the tailings dam for solid deposition. After 15 years (1982–1997) the uranium mining and milling operations have ceased. However, the chemical plant that treats the liquid effluent is still active. The effluent from the tailings dam is treated with $BaCl_2$ to remove radium isotopes from the solution. The solids (precipitate) settle in two holding tanks and the overflow is discharged into the environment. Average annual precipitation is 1800 mm/year.

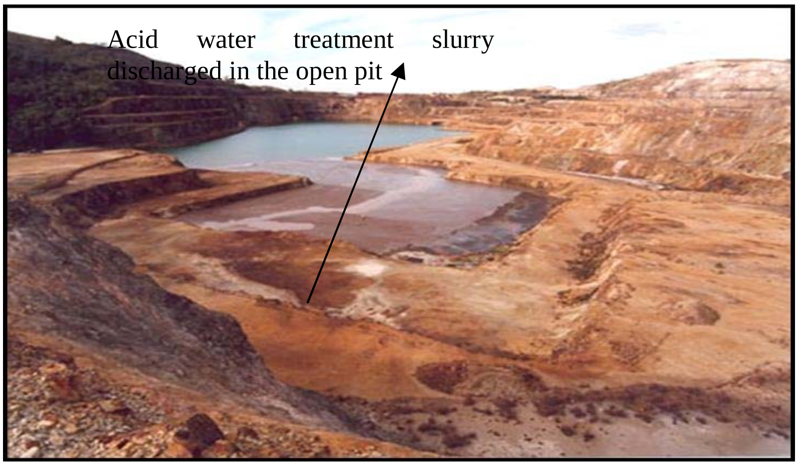

FIG. 2. Open pit with the deposition of the slurry from the acid water treatment in detail.

Table 1 shows the amount of waste rocks deposited in the different dumps; piles number 4 and 8 being the largest. These two piles together contain about 60% of the total amount of rocks removed during mining operations. The relevant aspect of the WRP 4 is that all the drainage percolating from the system is collected in a holding pond at the toe of the dump.

TABLE 1. OVERVIEW OF THE CHARACTERISTICS OF WASTE ROCK PILES (WRP)

WRP	Volume 10^6 m³	Surface Area 10^4 m³	Main Source of Material
1	4,4	25,5	Overburden
3	9,8	20,5	Overburden
4	12,4	56,9	Waste material from body B+Overburden
7	2,4	5,3	Overburden
8	15,0	64,4	Waste Material from body (B+E)+Overburden
WRP inside the mine pit	0,56	9,87	Waste material from body E

Table 2 shows the chemical composition of the effluents generated at the site. The presence of pyrite in the rock material explains the low pH values in the drainage. It can also be seen that uranium is being preferentially mobilized relatively to ^{226}Ra. Elevated concentrations of ^{238}U along with those of Al and F and the low pH values preclude the release of these drainages into the environment without prior treatment.

The occurrence of high radionculide concentrations in the drainage from WRP 4 was first reported by Amaral et al. [2]. Fernandes et al [3, 4] investigated the main processes responsible for pollutant mobilization and transport from the WRP 4 and provided for the adequate management of these drainages. The dissolution of K-feldspar and kaolinite, along with the oxidation of pyrite by O_2 and Fe^{3+} were simulated by means of geochemical modelling. The results revealed intrinsic oxygen rates (IOR) on the order of 10^{-9} kg(O_2)m^{-3}.s^{1}. It was estimated that more then 500 years would be necessary for the pollutant concentrations in the drainage to decrease to acceptable values. The significance of these findings to the management strategies is that permanent solutions will have to be applied instead of the collection and treatment scheme presently in place.

TABLE 2. CHEMICAL AND RADIOLOGICAL CHARACTERISTICS OF MILLING LIQUID EFFLUENT

Physico-Chemical Parameters	Ácid Water	Mill Tailings Pond Overflow	Environment Release	Release Limit
Concentration (mg.L^{-1})				
Mn	75	< 0,05	8,8	1,0
Fe	—	—	0,2	15,0
Al	96	—	9,8	0,1
Ba	—	—	0,3	—
MoO_3	—	—	—	—
ZrO_2	—	—	—	—
Ca	—	596	406	—
SO_4	—	1400	984	250
F	99	5-10	5.6	10
P_2O_5	—	—	—	—
pH	3,30	9-10	7.3	—
Radionuclide Activities (Bq L^{-1})				
U	175	0,4	0,32	0,4
^{228}Ra	—	<0,3	0,2	0,2
^{210}Pb	—	<0,2	<0,2	0,2
ThO_2	—	<0,02	<0,02	0,2
^{226}Ra	0,29	<0,2	<0,2	0,2

It has been estimated that in the period between 1982 and 1992 approximately 2.05 x 10^6 t of wastes were deposited in the tailings dam. The amounts of the different materials deposited in the tailings dam are depicted in Table 3. The average composition of the deposited wastes is shown in Table 4.

TABLE 3. INVENTORY OF THE WASTES DEPOSITED IN THE TAILINGS DAM

Material	Mass (ton)
Milled Ore	1,764,976
Sulphate	135,168
Pyrolusite	35,049
Phosphatic Rock	6,770
Lime	109,950
Total	2,052,913

TABLE 4. AVERAGE COMPOSITION OF THE WASTES IN THE TAILINGS DAM

Species	Concentration (%)
ZrO_2	0.15
MoO_3	0.02
Al_2O_3	23.4
K	11.2
SiO_2	54.0
CaO	0.25
SO_4^{2-}	2.3
S^{2-}	0.5
Fe_2O_3	3.9
Mn	0.02
P_2O_5	0.09
U	0.018
Th	0.004
^{226}Ra (Bq/g)	2.5
^{210}Pb (Bq/g)	3.4
^{228}Ra (Bq/g)	1.4

REGULATORY ENVIRONMENT

In Brazil a uranium mining and processing project needs to obtain the permits for operation from the Brazilian Institute of the Environment (IBAMA) and from the Brazilian Nuclear Energy Commission (CNEN). The later does not have specific/dedicated regulations to define to which requirements an operator should comply with in terms of decommissioning[‡] (closure) and/or environmental remediation[§]. In the existing regulations for obtaining the nuclear license the decommissioning/closure of a mining facility is treated as abandonment of the installation and requires the following actions:

- Backfilling the open pit or mine galleries (in case of underground operations) with mine debris and sealing of all wells, holes, galleries or any other excavation for research or ore removing, in the surface or sub-surface, to prevent the occurrence of accidents;
- Actions to limit the potential risks to the human health and safety;
- Classification of areas in the mine to avoid the release of toxic substances to the environment; and
- Execution of an abandonment and area remediation plan, to be approved by the Regulatory Authority (CNEN), where possible future uses shall be predicted.

These requirements are established in CNEN–NE–1.13 (www.cnen.gov.br) that regulates the licensing of uranium and thorium mining and milling facilities. Release criteria, however, are not provided but it is implicit that the releases into the environment shall not exceed those values authorized for the operation of the installation.

Specific regulations are however available for wastes dams systems containing radionuclides – Standard CNEN-NE-1.10 (www.cnen.gov.br). It is required that the wastes shall be stabilized physically and chemically in order to assure that effluents leaving the system comply with the acceptable regulatory levels. It is also stated that stabilization shall begin immediately after the termination of wastes deposition. The systems shall be provided with means to seal or eliminate contaminated drainage sources, in order to avoid, as much as possible, the collecting and treatment of the drainage. The system shall also be protected against the natural drainage by means of engineering works like dykes and embankments. It shall also be controlled and signalled in order to restrict the invasion of members of the public and to prevent non-authorized use of the wastes. The stabilization, control and maintenance of the system in the long term shall be documented and this document must be part of any commercial transaction involving the area. CNEN shall also be informed promptly about any new land owner.

Regarding the Federal Environmental Regulatory Authority (IBAMA) and in line to what is established in the part of the Brazilian Constitution that deals with the environment (article 225, paragraph 2); the Decree No. 97623 of April/10/1989 demands that every

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[‡] Administrative and technical actions taken to allow the removal of some or all of the *regulatory controls* from a *facility* (except for a *repository* or for certain *nuclear facilities* used for the *disposal* of residues from the mining and processing of *radioactive material*, which are 'closed' and not 'decommissioned').from IAEA Safety Glossary at http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf

[§] Any measures that may be carried out to reduce the *radiation exposure* from existing *contamination* of land areas through actions applied to the *contamination* itself (the *source*) or to the *exposure pathways* to humans.

existing project involving mineral extraction in the country should make available a “Area Remediation Plan” in no more than 180 days after the promulgation of the decree. The Decree has also established that in the case of new operations, the plan must be presented during the environmental licensing of the project. Economical aspects of the environment remediation are also taken into account and costs related to this activity must be part of the overall project cash-flow.

What can be concluded is that in terms of Environmental Remediation there are more defined legal requirements from the Federal Environmental Regulatory Authority (IBAMA) than within the Nuclear Regulatory Authority (CNEN).

This is why IBAMA has requested the operator to sign a Term of Environmental Compliance (TEC) in which a Remediation Plan needed to be prepared and approved not only by IBAMA but also by the other intervening authorities (i.e. CNEN and the State Environmental Authority). As a part of the TEC a Term of Reference (ToR) was developed, mainly by the Institute of Radiation Protection and Dosimetry (IRD) that at that time was functioning as a technical supporting institution of the CNEN Directorate of Radiation Safety (DRS). The ToR was based on the international experience and on publications of the International Atomic Energy Agency[**] and dictates all the relevant aspects/requirements the operator has to comply with in the preparation of the environmental remediation plan.

REMEDIATION STRATEGY

In order to cope with the requirements established in the TEC, an overall remediation strategy had to be developed. The plan is to be presented by the operator and should be compatible with the local ecosystem, taking into account possible future land uses. It was agreed between the regulators and the operator that the plan to be presented would be divided into four parts:

(1) tailings dam and its area of influence;
(2) waste-rock dumps;
(3) open pit; and
(4) industrial Area (considering the dismantling of buildings as well as the decontamination of equipment and general material. The specification of the clearance levels was also to be fixed by the operator but needed approval from the Nuclear Regulatory Authority- CNEN.

For each one of the above items, the plans will have to be detailed in such a way that the intended objectives need to be specified as well as the intended strategies and expected performance. Cost effectiveness analysis will have to be presented as well. Physical and financial schedules will have to be discriminated in such a way that the regulators may monitor each of the on-going activities.

[**] Guidebook on Good Practice in the Management of Uranium Mining and Mill Operations and the Preparation for their Closure. IAEA SAFETY REPORT Series No 1059 (http://www-pub.iaea.org/MTCD/publications/PDF/te_1059_prn.pdf

SELECTED STRATEGY

The existing situation combines two of the most relevant issues in remediation programs, i.e., lack of consistent environmental management strategies that considered the closure and environmental remediation of the site from the beginning of operations and constraint of resources (both human and financial). Also, the absence of local expertise in the remediation of uranium mining sites will lead the operator to request some sort of support from international organizations. Probably, a phased approach will have to be put in place. It means that a substantial part of the site may (or will) be released prior to the end of institutional control of the whole area. The concept of a phased approach is the rationale for the division of the whole site in the four above mentioned areas. Site categorization according to the operation history and/or the likelihood of contamination will be of key importance in this process. Office areas, restaurant, library, and even the sulphuric acid plant for example are not expected to contain any residual radioactivity, or at least may contain levels of residual radioactivity at very small or negligible fraction of the release criteria to be adopted. On the other hand, areas where mining and milling wastes were disposed will have to be dealt with special consideration, and due to the long half-lives of the involved radionuclides will be unavoidably subjected to further institutional control.

As it has been mentioned above, the remediation plan is to be presented by the operator. Nevertheless, the Regulatory Authority through the Institute of Radiation Protection and Dosimetry, in a proactive way has been developing basic research and technical studies to support the decision making. As a result of this work a preliminary conceptual plan has been developed (without meaning an official position about the situation). It involves steps that tackle legal/operational, technical and financial approaches:

- The first step involves an administrative arrangement that encompasses the formation of a working group to be composed by the consultant company (in charge of proposing the remediation plan in agreement with the mine operator); the regulatory federal and state authorities (CNEN, IBAMA, FEAM); representatives of local stakeholders and technical institutions (national institutes; universities, etc). These last institutions could provide manpower to carry on field work, like monitoring, data collection interpretation, modelling, etc as students could develop their thesis in the area. This would also ensue, at least at some extent, some sort of technology transfer. Periodic meetings will allow for the monitoring of the overall work, the discussion of the obtained data, correction of any misleading course of action, trust building within the involved parties and avoidance of further delays in the concession of permits. Stakeholders' involvement is also of key importance to avoid the further rejection of any remediation strategy to be selected.
- From the technical point of view, the abatement of acid drainage generation is of primary importance as it will avoid the accumulation of residues that need to be managed adequately. As it has been predicted the acid drainage will last for centuries and the collect and treatment strategy can not be faced as an acceptable solution. In addition to this, presently the slurry from acidic waters treatment is being disposed in the mine pit, as the operator is no longer allowed to deposit any further waste/residues in the tailings dam. Dealing with acidic drainage abatement will also allow for the beginning of procedures addressing the closure of the tailings dam that will involve dewatering, reshaping and solid consolidation prior to the application of a dry cover.
- Meanwhile, the dismantling of the non-contaminated premises can take place with the transfer of equipment and machinery to the other production centre of the

company located at Caetite (north-eastern region of Brazil). It has to be stressed that at the mining site of Caetite uranium is produced by the heap–leach process. However, plans exist to increase uranium production at that site due to the foreseen increase in uranium demand caused by the probable construction of the third nuclear power plant in the country. The need to production increase will then justify the implantation of a conventional leaching plant to which the materials from the Pocos de Caldas facilities can be transferred.

- Alternative course of action in the phased approach would involve the use of the former industrial area, with the appropriate adaptation, to process uranium from different sources or to produce rare earth concentrates. This strategy has the advantage that the site already store radioactive waste. However this strategy faces strong opposition of pressure groups that understand that it simply implies the transference of "radioactive wastes" from other parts of the country to Pocos de Caldas site. A negative aspect is that it would also involve the commissioning of another tailings dam.
- Recovery of uranium from the acidic waters may also play a role in the remediation scheme. Preliminary feasibility studies regarding the recovery of uranium from acidic waters have shown (as it will be demonstrated further in this text) that about 30 ton/year of U_3O_8 can be recovered. With the increasing prices of uranium in the international market this may end-up as being an attractive approach. Revenues from this strategy would be used in the remediation of the site.

TECHNICAL ASPECTS AND COSTS OF THE REMEDIATION OPTIONS

Waste-Rock Piles

Removal of the source, i.e., returning the waste-rock material (and eventually the tailings) back to the open pit has been examined as a possible solution. The costs related to this option based on MEND [5] are: hauling of the materials –$1.5/ton.rock; landfill operations – $3.0/ton.rock and revegetation – $5000/ha. A rough estimation of the overall cost for this option, taking only into account the material deposited in the WRP 4, would be about $70 million. This seems to be a very high expenditure, therefore this option would not be recommended as an effective strategy to remediate the site.

Immobilization techniques may be effective in reducing migration of radionuclides from tailings, but not from the waste-rock piles. In addition, radon exhalation and gamma exposure would not be addressed by this strategy. As a result of the above considerations, capping would be the preferred strategy. In order to evaluate the effectiveness of capping in the attenuation of acid generation, modeling exercise had to be implemented. First, one has to take into consideration that acid drainage is a result of pyrite oxidation. The supply of oxygen is the limiting force in pyrite oxidation. Bacterial activity may also play an important role in the process (equations 1 and 2).

$FeS_2 + 8H_2O + 14\ Fe^{3+} \rightarrow 2SO_4^{2-} + 15\ Fe^{2+} + 16H^+$ (equation 1)
$Fe^{2+} + ¼\ O_2 + H^+ \rightarrow Fe^{3+} + ½\ H_2O$ (equation 2).

The oxygen removed from the system in the process of pyrite oxidation will create a concentration gradient in the rock pore spaces. A high oxygen demand will promote a pressure gradient inside the pile that will lead to the transport of the air mass into the pile as a result of oxygen removal. At lower oxygen demands the transport of oxygen will be governed by diffusion. Ritchie [6] introduced the concept of IOR, which is simply the rate of oxygen consumption in the material forming the pile in its prevailing conditions. The most practical unit to express the IOR is kg $(O_2)m^{-3}\ s^{-1}$. Table V shows some values of IOR and relevant characteristics associated with these values.

In the case of the WRP 4, it has been demonstrated by Fernandes and Franklin [7], that IOR values of the order of 10^{-9}kg $(O_2)m^{-3}.s^{-1}$ are found. In such a situation diffusion dominates the process. Providing more oxygen to the system, in an attempt to speed up the oxidation process will not be an effective strategy since not all the oxygen provided to the system would be consumed under these conditions, i.e., low IOR values. In such cases capping the waste-rock pile with a material with a lower oxygen diffusion coefficient than the rocks forming the pile would be an effective manner to halt the input of oxygen into the system and consequently reduce the concentration of pollutants in the drainage. According to Ritchie [8] the attenuation factor will depend more on the properties of the capping material than on the properties of the waste material. The practical problem to be addressed is to design an appropriate capping system in such a way that its physical stability can be maintained in the long term. For a cap of inactive material with thickness equal to X_c and diffusion coefficient D_c the oxidation rate can be determined using the following expression [8].

$$GOR = \sqrt{2C_0 DS^*}\,(\sqrt{\alpha + n} - \sqrt{\alpha + n - 1}) \text{ (equation 3)}$$

where

$$\alpha = \left(\frac{X_c}{D_c}\right)^2 \left(\frac{S^* D}{2C_0}\right) \text{(equation 4)}$$

GOR = Global Oxidation Rate ($kg_{O2}m^{-2}.s^{-1}$)
X_c = thickness of the inactive material cap (m)
S* = Intrinsic Oxidation Rate ($kg_{O2}.m^{-3}.s^{-1}$)
C_0 = oxygen concentration in air ($kg.m^{-3}$)
D = total oxygen diffusion coefficient in the pile ($m^2.s^{-1}$)
D_c = oxygen diffusion coefficient in the cap material ($m^2.s^{-1}$).

TABLE 5. SIGNIFICANCE OF THE IOR VALUE MAGNITUDE

IOR kg $m^{-3}s^{-1}$	Time for pyrite consumption (year)	Time for the consumption of rock bearing carbonates	Time for the consumption of O_2 initially present in rock pore spaces	Heat Generation Rate (W m^{-3})	Sulfate concentration in the drainage (mg/L)	Relevance of the IOR
10^{-5}	0.167	2.4 d	-	129	-	Rate observed in laboratory experiments of biological oxidation
10^{-6}	1.67	3.4 w	0.9 d	12.9	-	Rate necessary for running bio-oxidation heaps.
10^{-7}	16.7	0.66 y	1.3 w.	1.29	-	Effective extremely high rates for some waste-rock piles.
10^{-8}	167	6.57 y	13.1 w	0.129	21,600	Rate typically found in waste-rock piles
10^{-9}	1,670	65.7 y	2.52 y	0.013	2,160	Typically low rates found in some waste-rock piles
10^{-10}	16,700	657 y	25.2 y	-	216	Rate associated with marginal environmental problems

Source (Ritchie, 1995)

With the aid of equation 4, values of GOR were simulated as well as the sulfate load for different capping thickness while varying values of oxygen diffusion coefficients. It was assumed that the infiltration rate would be of the order of 50% of the total precipitation (equivalent to 0.85 $m.a^{-1}$). It has been demonstrate however, that the infiltration rates may be reduced to values as low as 1 to 5% of the total precipitation rates with an effective capping. The resulting values are pictured in Figure 3.

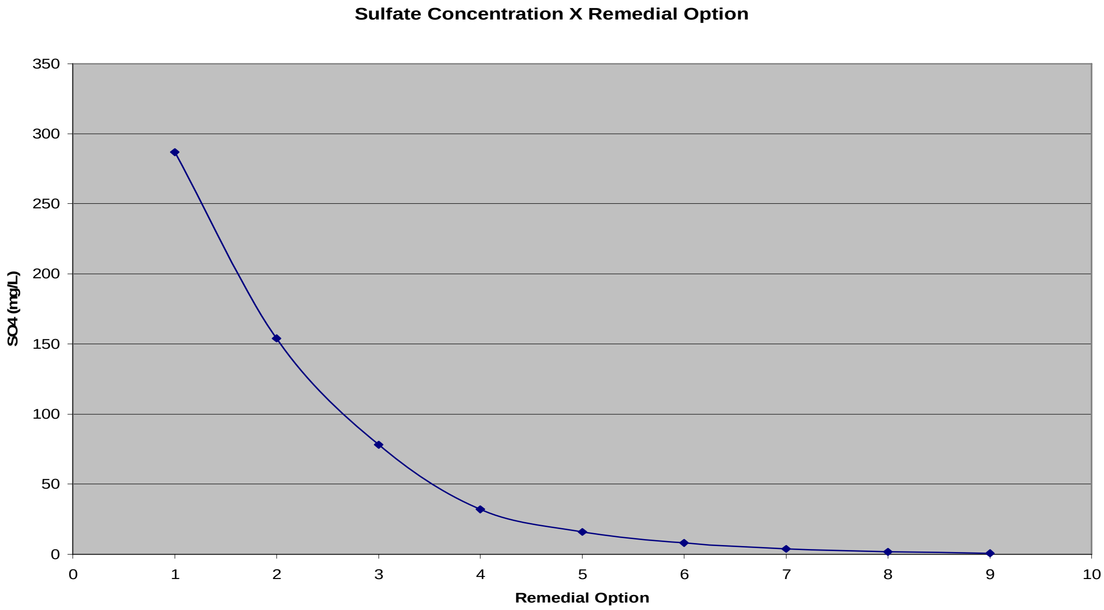

FIG. 3. Sulfate concentration x Remedial Option.

It is well known that costs of remediation increase linearly with the attenuation of the environmental impacts. Figure 3 suggests that capping the waste rock pile 04 with a material with an oxygen diffusion coefficient of 10^{-9} $m^2.s^{-1}$ and a thickness of 0.5 m (option 4) would be the most effective solution to reduce the concentrations of pollutants in the drainage leaving the system because increasing the thickness of the capping material or using materials with lower oxygen diffusion coefficients would not be more effective than what is obtained from option 4. Regarding ^{238}U activity concentrations, it was assumed that the radionuclide varies linearly with sulfate as suggested by Fernandes and Franklin [7]. If the same reduction level is applied to the other pollutants (e.g. Al and F) the concentrations in the mixing zone of the receiving water body will be lower than the Brazilian legislation standards.

One of the issues regarding the capping of waste rock piles has to do with the erosion of the capping material. If clay is used as the capping material some sort of protective barrier should be applied. A general scheme to be put in place in those situations is a three layer barrier consisting of a bottom granular layer, an intermediate one – the capping material itself, and a third layer consisting of gravel to protect the capping layer against erosion. The total cost would be about US$ 10 million for the remediation of only one of the existing waste rock piles in the Poços de Caldas mining site. These costs may be reduced if a less costly capping material (clay) can be obtained from neighbor areas.

Harries [9] reports that rehabilitation costs at the Woodlawn site in Australia, with similar problems to those of Poços de Caldas were of the order of $22 000/ha. IAEA [10] reports that decommissioning strategies adopted in different countries show average capital costs in the range of $3 to 15 million depending on the complexity of the installation. Reported costs for remediation of waste rock piles were $0.30/ton of deposited material. Applying this figure to waste rock pile 04 we would have a value of about $7.0 million, which is parallel with the estimated costs presented here.

Another strategy that could be applied to mitigate the impacts of acid drainage generated by pyrite oxidation in waste rock pile 04 would be the economical recovery of uranium present in the drainage. As mentioned above, presently, these drainages, along with the drainage from the other waste rock piles are being pumped to three main ponds and then neutralized with lime. The resulting slurry is deposited in the open pit. It can be estimated that approximately 30 t of ^{238}U are disposed as waste per year. This figure represents 30% of the average annual production of the Poços de Caldas facility. The challenge here is to establish an efficient way to extract uranium from these waters. An ionic exchange technique has been adopted in similar situations elsewhere and is a mature technology. The most important exchangers use synthetic polymers to which the active functional groups are attached. Ionic inorganic exchangers, or zeolites, are also available [5]. Critical to the success of ionic exchange resins in treating acid drainages is to identify the exchangers that will exhibit a specific selectivity for the metal of interest over those that are not to be separated like Fe, Al and Ca. MEND [5] makes an assessment of the removal of metals from acid mine drainage. It is concluded that most of the investigated resins do not show a well-defined selectivity for the metals of interest – Sb, Cd, Cu, Ni and Zn – and that only the co-extraction of Fe was an obstacle for the application of resins to acid drainage.

The use of ionic exchange resins in the extraction of uranium from water has been reported by several authors [11, 12]. Naden et al [13] estimated that capital costs involving the construction of an ion extraction plant would be about $1.6 million.

The proposed scheme to be applied in the case of the Poços de Caldas site would have to include the removal of iron from solution. That should be achieved by means of the aeration of the solution and the elevation of the pH to 4.5. If it is assumed that the process has an efficiency of 90% and if the costs of uranium in the international market are taken into account, i.e., $100/kg , it can be roughly estimated that about $6.0 million would be gained with the recovery of uranium from the acid drainage. It was reported by the operator that about $2.6 million were spent on water treatment or approximately $145 000 per year. As a result it can be proposed that the revenue obtained with uranium recovery could be deposited in a fund to be used in future remediation of the site.

Tailings Dam

The oxidation of the residual pyrite remaining in the milled ore also results in acid generation in the tailings environment similarly to what happens in the waste rock piles. Fernandes et al. [14] described the main geochemical mechanisms taking place in the tailings environment. It was suggested that oxygen diffusion would be taking place through the first 1-m layer of the tailings. Metals like Fe, Al and U would be transported downward by the percolating waters but Ra isotopes and ^{210}Pb would not. In this upper zone, pH would be as low as 3.0. However, pH values increase with depth (varying in the range of 5.0 to 6.0). This is a consequence of the introduction of the milling effluent with high pH values (in the range of 10 to 12) during the operation of the industrial plant. It has been postulated that this region of the tailings dam would function as a buffering zone that would neutralize the acidic percolating waters moving downwards. As a result, the migrating elements would precipitate in this higher pH zone. It was also estimated that the release of untreated effluent into the environment, would result in doses as high as 8.0 mS/y to members of the potentially most exposed population group. This value is unacceptably higher than the primary limit established by the Brazilian regulatory authority, i.e., 1.0 mS/y and the dose constraint of 0.3 mSv/y.

Regarding the remediation of the tailings dam, capping seems to be the most appropriate course of action. Capping will reduce radon emissions, will shield against the exposure to gamma radiation and additionally will prevent the diffusion of oxygen into the tailings. As a result, oxidation of pyrite will be reduced.

The computational code RESRAD [15] was used to examine the effect of application of a cap material over the tailings. As input data, a material with the same properties as that used in the waste rock remediation was tested, i.e., a material with an oxygen diffusion coefficient of 10^{-9} m^2-s^{-1}. It was assumed that radon gas would be diffusing through the cover at rates equal to oxygen. It was observed that the cap would reduce the doses (both exposure to radon and gamma radiation) to values virtually equal to zero. The increase after 1,000 years would be due to the erosion of the cap material. In the absence of site-specific information the erosion rate of 6.0 x 10^{-5} $m.a^{-1}$ was adopted. According to Yu et al [15] this value would be typical of a soil not subjected to any agricultural practice. Values in the range of 10^{-7} to 10^{-4} $m.a^{-1}$ are reported in the literature and depend, besides the vegetation, on the slope of the land, its use and type of cap material.The costs associated with this strategy are estimated as being of the order of approximately $3.7 million if the same scheme used in the application of a cover in the waste rock pile 04 is adopted in the tailings dam. Additional geotechnical work would be required for the tailings dam, and this additional work may result in extra costs not projected in this work. Details of the application of a dry cover to a tailings dam can be seen in Leoni et al. [16].

CONCLUSIONS

This paper tried to address the challenges to be faced in the closure and environmental remediation of the Uranium Mining Site of Pocos de Caldas. It has been demonstrated that this project involves technical, financial, political and social aspects, all of them interacting with each other. As a result good planning needs to be put in place and arrangements need to be found in such a way that a positive atmosphere that will lead to the appropriate interaction of the relevant players is created.

As per the situation in Brazil, international support, in order to bring expertise of those already familiar with the elements of uranium mining closure and remediation, will contribute to the achievement of good results. However, this relationship must take place under a perspective of technology transfer, taking into account that the country is operating another production centre and another one is to be started in the near future.

From the technical point of view it has to be recognized that the greatest challenge to be faced by the operator will be the abatement of acid drainage coming from the waste-rock piles. Addressing this issue properly is very important for the overall success of the remediation activities. Not to mention that acid drainage is not an issue related only to the waste-rock dumps but also affects the tailings dam. As an alternative to the remediation of the wate-rock dumps, attention must be given to the possibility of recovering uranium from the acidic waters. However, it is important that the operator sees this potential source of revenue as to generate resources to be invested in the remediation of the site.

If on the one hand the Regulatory Authority has invested in the preparation of human resources to face the challenges of the closure and clean-up of the site through one of its institute – the IRD – on the other one the operator must be prepared to understand all the relevant issues involved on these operations and by doing so be able to discuss with future contractors and also with the other relevant stakeholders (i.e. regulators, local community, NGO's, etc). The support of international organizations like the International Atomic Energy Agency is instrumental to make available international experts and support scientific visits of the operator staff to visit sites that have developed projects of closure and environmental remediation.

Finally, it can not be forgotten that the implementation of a good and effective communication program will be of fundamental importance to facilitate the understanding of the goals and objectives of those activities by laypersons. This will of course avoid unnecessary expenditure of resources that will be eventually allocated in activities that will not improve the overall safety conditions of the site but will basically address unjustified and subjective (although) important concerns of the population.

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DECOMMISSIONING OF ELLIOT LAKE URANIUM MINES – SITE PERFORMANCE AND LONG -TERM RADIUM MOBILITY

N. K. Davé
Mining and Mineral Sciences Laboratories, CANMET, Natural Resources Canada, Ottawa, Canada

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Abstract

Low ore grade and uranium market conditions led to the closure of all uranium mines in the Elliot Lake region of north-central Ontario, Canada. This was followed by rehabilitation and decommissioning of all previously closed, inactive (past historic) and recently closed-out mines and associated waste management facilities in accordance with the licensing requirements of the Canadian Nuclear Safety Commission (CNSC). Acid mine drainage and contaminant migration, including uranium decay series radionuclides and trace heavy metals, from waste management areas are major environmental concerns at many of these sites. Hence, long term prevention, control and treatment measures are required.

In the past, many older and inactive surface-deposited waste management sites, having acidic drainage problems, were rehabilitated with vegetation covers. This has controlled surface erosion and greatly improved site aesthetics. However, acidic drainage continues at these sites and long term effluent collection and treatment measures are required. The waste management areas at the newer, recently closed mines have been rehabilitated with shallow, in situ water covers, having a minimum depth of approximately 1m, to minimize acid generation and release of radon gas and its progeny. Acid generation at these sites has decreased significantly and at most sites only a limited effluent treatment is required for pH control and radium removal.

The mobility of Ra–226 from pyritic uranium tailings was evaluated for both on-land and underwater disposal scenarios. During the acid generation phase and/or in the presence of available sulphate ions, the dissolution and mobility of radium was very low due to sulphate ion solubility control. With the cessation of acid generation, and/or upon depletion of sulphate ion control, including microbial sulphate degradation, the solubility of radium was enhanced. Hence, further investigations are needed to improve the understanding of the long term stability and control aspects of decommissioned uranium mine waste management sites.

INTRODUCTION - URANIUM MINING HISTORY OF ELLIOT LAKE

The Elliot Lake-Blind River region of north-central Ontario, Canada, was a major uranium producing district during the 1950s to 1980s. Initially, during the mid 1950s to early 1960s, uranium was mined for the US nuclear and western defence programs. This resulted in the opening of a total of 14 small and medium-sized mines and 10 uranium milling plants in the region, as shown in Figure 1.

Uranium ore bodies mined in the region were low grade, containing approximately 0.1% U. The ore, hosted in a quartz-pebble conglomerate, contained some sulphide mineralization, mostly that of iron and some trace heavy metals. Most of the uranium mines in the area were closed and the facilities abandoned in the early 1960s due to the cancellation of the uranium delivery contracts by the US Department of Energy. The remaining mines in the region were consolidated in the late 1960s to early 1970s and uranium production stabilized to meet the increasing demand of the nuclear power generation industry.

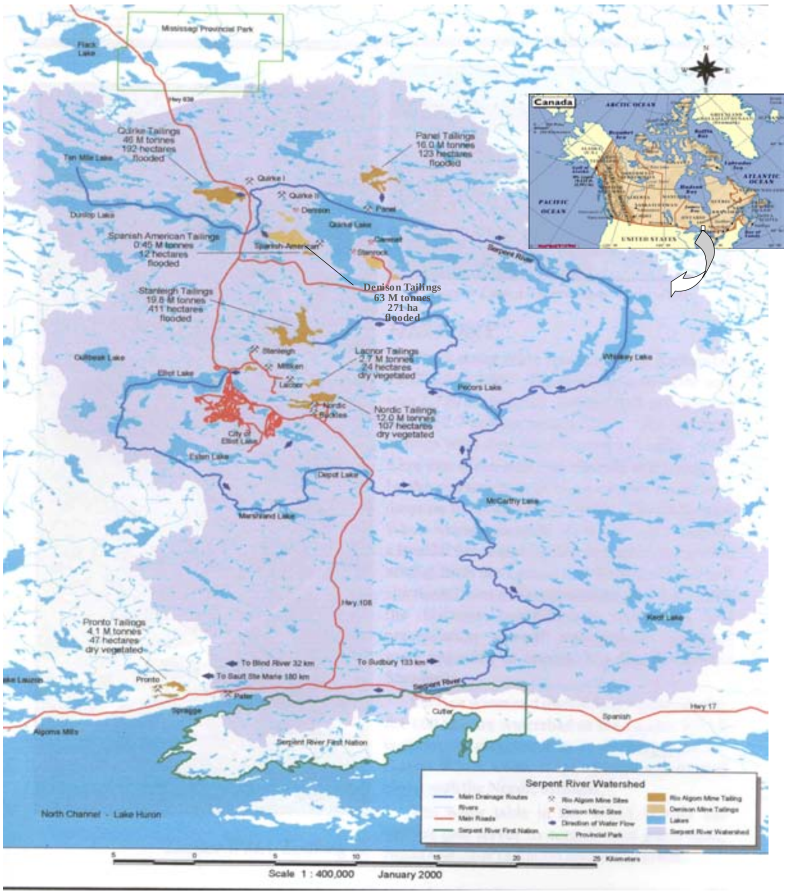

FIG. 1. Locations of uranium mines/mills and waste management facilities in the Elliot Lake-Blind River region of north-central Ontario, Canada.

Economic realities of low-grade ore and uranium market conditions led to the cancellation/non-renewal of several long term uranium delivery contracts for the uranium mining companies in the Elliot Lake region. Consequently, all low-grade uranium mines closed during the early 1980s to mid 1990s.

The Canadian *Nuclear Safety and Control Act* (NSCA) requires that all uranium producing, processing and waste storage facilities, including active, inactive and abandoned sites be licensed by the Canadian Nuclear Safety Commission (CNSC). The licensing of inactive and abandoned (past historic) sites is required to enable the CNSC to ensure appropriate financial guarantees, where deemed necessary, covering the decommissioning and subsequent management of the waste sites [1].

The CNSC licensing requirements resulted in rehabilitation and decommissioning of all previously closed, inactive and recently closed uranium mines in the Elliot Lake-Blind River region. This paper reviews the status of decommissioning of uranium mine, mill and associated waste management sites and outlines potential long term environmental issues associated with uranium mine decommissioning.

URANIUM MINE/MILL REHABILITATION AND DECOMMISSIONING

All uranium mine, mill, processing and waste management facilities that have been inactive or recently closed are classified according to the following two categories:

- past historic sites, and
- newer mine sites.

The past historic sites are those that operated and closed during the early period of uranium mining, from the 1930s to 1960s and have been inactive for the past thirty years or so. Many of these mines operated during the period when environmental regulations were non-existent, were operated by small or junior mining companies and abandoned upon cessation of mining activities. The past historic and inactive sites that are owned and operated by their original or new private-sector owners have all been properly rehabilitated and decommissioned. These sites are on care and maintenance and are managed by their owners/operators according to the past-historic site licensing requirements.

The newer sites are those that ceased operation in the early to mid 1990s. These sites have been properly rehabilitated and decommissioned in accordance with the new CNSC licensing requirements. Presently these sites are in a transition phase of monitoring, and care and maintenance.

DECOMMISSIONING OF HISTORIC WASTE SITES - VEGETATION COVER

These uranium mine/mill and waste management facilities, which operated during the 1950s to 1960s, have been all rehabilitated and are managed by their current owners/operators. These mine and waste management facilities are licensed by the CNSC as historic waste sites and are on care and maintenance basis and managed accordingly. Nine of such sites are located in the Elliot Lake area, which include: Nordic, Lacnor, Pronto, Milliken, Spanish American, Sheriff Creek, Buckles, Canmet and Stanrock (Figure 15). In addition, two small wetland sites containing partially submerged tailings at Panel Wetlands and Lower Williams Lake have been included as parts of extended waste management facilities of nearby Panel and Denison waste management sites. All uranium mine tailings in the Elliot Lake area are acid generating, containing approximately 5-10% pyrite.

The detailed site description and summary of rehabilitation and decommission activities conducted at two of the inactive sites at Elliot Lake, namely Nordic and Stanrock mines are provided below. These sites are illustrated for their diversity in past operational, management and decommissioning history.

Nordic mine/mill and waste management sites

The Nordic mine, located approximately 5 km east of the city of Elliot Lake, operated from 1957 to 1968 and produced approximately 12 million tonnes of acid generating tailings containing ~5–10% pyrite. An acid leach process was used in milling and the tailings were neutralized to a pH of ~ 8.5 prior to their discharge in a land base, above grade, waste management facility. Most of the tailings are contained in the larger Nordic Main area with a smaller proportion deposited initially in the Nordic West Arm extension of the main tailings area. The surface deposited tailings area covers approximately 107 ha and is impounded by perimeter dams along the southeast, south and west sides.

The tailings site was extensively used in the past for environmental research in the areas of vegetative reclamation, acid generation, and contaminants migration and uptake via various environmental pathways. The tailings surface was successfully revegetated and rehabilitated in the mid 1970s, and the site has been one of the best revegetated sites in Canada for the past 35 years or more, as shown in Figure 2.

A full scale rehabilitation of the site was done in the mid 1990s. The mine/mill complex and ancillary facilities at the site were removed. The shaft and all opening to underground workings were sealed and capped with cement pads. All contaminated materials at the mine/mill site were relocated to the waste management area, excavated areas backfilled and covered with a layer of clean sand or till and the site was vegetated. Dams and effluent treatment facilities at the site were upgraded in 1998-1999.

The site is presently managed on a care and maintenance basis [2]. Surface run-off and seepage from this site and from the upstream located Lacnor waste management facility are collected and treated at the Nordic effluent plant. The treatment sludge is allowed to settle and is stored in the nearby North Nordic Lake sludge management facility.

FIG. 2. Rehabilitated Nordic mine and waste management facilities, Elliot Lake, Ontario, Canada.

Stanrock mine/mill and waste management sites

The Stanrock mine, located approximately 20 km northeast of the city of Elliot Lake, operated from 1957 to 1968 and produced approximately 8 million tonnes of acid generating tailings containing ~ 5–10% pyrite. The milling process also used acid leaching and the tailings were neutralized prior to their disposal in a surface based waste management facility. The site covers an area of approximately 71 ha and also contains tailings discharged from a nearby Canmet mine. Originally, the tailings were impounded by extensive dams, constructed of coarse cycloned tailings, on the east, south and west sides. This resulted in breach of dams and spillage of some tailings outside the containment area in the past. Excepting some experimental vegetation trials and other surface stabilization and rehabilitation studies, the surface of the tailings remained exposed and un-reclaimed. The site was kept pending for disposal of additional tailings from future mining operations. Figure 3 shows the Stanrock tailings site before and after decommissioning.

The mine/mill complex at the site was removed and the area rehabilitated during the early 1990s. The waste management site was rehabilitated during 1997 to 1999 by constructing new, till-cored engineered dams immediately downstream of the original containment dams. These low permeability dams were designed and constructed according to new and applicable dam construction codes, and keyed onto the grouted basement rock (bedrock). This was done to facilitate the rise of the water table to near the tailings surface and above the un-oxidized tailings zone in the basin, thus minimizing further oxidation of the tailings, and at the same time providing radon exhalation control. A new effluent treatment facility was constructed at the site in 1998 and the tailings surface was vegetated during 1998–2000 [3]. Water cover at the site was considered during the planning stage of decommissioning, but it was deemed to be unfeasible and too expensive given the topographical conditions at the site.

FIG. 3. Stanrock waste management facility before and after rehabilitation, Elliot Lake, Ontario, Canada.

The site is currently managed on a care and maintenance basis. The effluent from the site is collected and stored in a holding facility for treatment on a seasonal basis, or on demand as and when required, depending upon effluent discharge flow and loading conditions.

DECOMMISSIONING OF NEWER MINE SITES – WATER COVER

Mines that ceased operation during the early to mid 1990s, though some of them have been operating since the mid 1950s, are closed out and decommissioned according to the new CNSC licensing requirements. Four of such mines, namely Quirke, Panel, Denison and Stanleigh mines, are located at Elliot Lake, Ontario (Figure 4). While Quirke, Panel and Denison mines ceased operation during 1990 to 1992, the Stanleigh mine was closed in 1996. With the closing of its last operating mine, the uranium mining era in the Elliot Lake region, known popularly as the uranium capital of the world, came to an end. These mine sites have extensive waste management areas comprised of acid generating tailings containing ~ 5–10% pyrite. Acid mine drainage (AMD) is a major issue of environmental concern at these sites.

In the past, the surface deposited tailings and waste rock sites were rehabilitated with a vegetation cover (e.g. Nordic tailings site), but the expected benefits of the cover in controlling acid generation and release of contaminants were not realised. Thus, for controlling acid generation at the newer sites, the waste management areas have been rehabilitated to provide a shallow, in situ water cover having a minimum depth of approximately 1m on top of the submerged tailings. Water has a low oxygen solubility of 8-10 mg/L compared to~285mg/L in air (20% oxygen concentration) and a low diffusion coefficient for molecular oxygen of~$1x10^{-9}m^2/s$ compared to~$1.8x10^{-5}$ m^2/s in air. Thus, where site climatic and topographic conditions are favourable, a water cover provides the most economical and natural cover for controlling acid generation in situ. The details of site rehabilitation and decommissioning of four such mine sites, namely Quirke, Denison, Panel and Stanleigh are provided below.

Quirke mine/mill and waste management sites

The Quirke mine located approximately 14 km north of the city of Elliot Lake, Ontario, operated from 1956 to 1961 and again from 1968 to 1990. It produced approximately 42 million tonnes of acid generating tailings and 4 million tonnes of waste rock. Upon cessation of mining, the rehabilitation and decommissioning activities at the mine site, including establishment of a shallow water cover on the tailings, started in 1992. All the buildings and ancillary facilities at the mine site were removed and all mine openings and shafts were sealed and capped with cement pads. All contaminated materials, soils and acid generating waste rock were hauled and deposited in the waste management area. The mine site was rehabilitated by covering with a clean till/sand fill and revegetated.

The tailings and waste rock were placed in a 192 ha tailings management area (WMA), located in a valley containing east-west trending ridges and impounded by low permeability containment dams. The acid generating waste rock was used to construct internal haulage roads and dykes within the waste management facility. The waste management area has an elevation difference of approximately 15 m along the east-west direction, which made it difficult to establish a single elevation water cover. The site was thus divided into five cells by internal dykes in a terraced configuration to provide the required water cover at five different elevations, as shown in Figure 17. The internal dykes have fine tailings and till layers on upstream sides to minimize seepage losses through them. The perimeter containment dams are engineered, clay-core-earthfilled dams keyed onto the grouted bedrock surface at the bottom. At the main eastside dam, where the bedrock was too deep, a vertical bentonite grout curtain as a cut-off wall was also constructed below the dam between the clay core and basement rock, to minimize seepage losses [1][4][5].

FIG.4. Rehabilitated Quirke mine/mill and waste management areas, Elliot Lake, Ontario, Canada.

The water cover in the WMA is maintained by natural precipitation and runoff from the catchment area of the site and by diversion of surface discharge flow from an upstream located Gravel Pit Lake. The water level in the Gravel Pit Lake is maintained approximately 3m above the maximum water elevation in the WMA. This facilitates a gravity inflow from Gravel Pit Lake to the WMA, at the same time maintaining a higher hydraulic pressure head in the lake to minimize seepage of contaminated porewater from the WMA to the lake.

Prior to the establishment of the water cover, the surface of the tailings in the WMA was leveled and agriculture grade limestone was incorporated into the exposed tailings surface to neutralize existing and any potential acidity generated during and after establishment of the water cover. Hydrated lime slurry is periodically added to the various cells, as and when required, to maintain nearly neutral pH conditions in the surface water cover. The water quality in upstream cells of the WMA is close to discharge quality levels, but flushing of previously accumulated acidity and oxidation reaction products is occurring from upstream to the downstream located cells. The effluent from the last cell is treated for controlling pH, dissolved metals and radium prior to its discharge. Presently the site is in a transition phase of treatment, monitoring, and care and maintenance.

Denison mine/mill and waste management sites

The Denison mine, located approximately 16 km north of the city of Elliot Lake, operated from 1957 to 1992, and produced approximately 63 million tonnes of acid generating tailings containing~5–10% pyrite. The tailings were placed in two tailings areas, TMA-1 and TMA-2, located in several former lake basins in a valley. TMA-1 lies immediately south of TMA-2 and is surrounded by east-west trending ridges and five engineered, low permeability dams. TMA-2 is located in a northwest trending valley and its outflow is directed towards TMA-1. The total surface area of the WMA is approximately 271 ha. Figure 18 shows the Denison mine, mill and WMA sites before and after rehabilitation.

The rehabilitation and decommissioning of the mine and WMA started in 1992 and completed in 1996. This consisted of removal and decontamination of sellable assets, removal of buildings and ancillary facilities including headframes, concentrators, workshops and building foundations etc. All contaminated materials at the site were removed and placed underground or buried at designated landfill locations within the WMA. All openings to the underground workings including mine shafts, adits and other mine portals were sealed and capped with concrete. The area around the mill complex was re-graded, covered with a layer of clean till, soil and overburden materials, when and where required, and the site was vegetated with local and agronomical species of grasses and legumes [3].

For providing single elevation water covers in TMA-1 and TMA-2, the tailings in TMA-1 were dredged from a higher elevation on the east side to below the expected final water elevation in the basin, and deposited in the deeper western part of the basin. The downstream perimeter dam in TMA-1 was reinforced and strengthened. The height of the low permeability west dam in TMA-2 was raised to divert the surface water flow from TMA-2 to TMA-1. The tailings above the anticipated final water elevation in TMA-2 were excavated or removed by hydraulic monitoring and placed in TMA-1 and underground. While removing the exposed tailings, lime was incorporated into the surface of the relocated and disturbed tailings in TMA-1 and TMA-2 to neutralize resident and potential future acidity. Figure 5 shows the Denison mine and WMA sites before and after rehabilitation.

FIG. 5. Denison mine/mill and waste management sites before and after rehabilitation and decommissioning, Elliot Lake, Ontario.

The water covers in the two TMA's are maintained at near neutral conditions by periodically adding hydrated lime slurry or sodium hydroxide solution. The final effluent from TMA-1 is treated prior to its discharge on as and when required basis. The quality of the surface water cover in TMA-1 has improved significantly since the completion of the remediation work and only a very periodic treatment, especially during spring runoff, is required for pH control. However, treatment for controlling Ra–226 levels in the discharge effluent is still required. Similar to other decommissioned facilities, this site is presently under a transition phase of treatment, monitoring, and care and maintenance.

Panel mine/mill and waste management sites

The Panel mine site and WMA are located approximately 23 km to the northeast of the City of Elliot Lake. The mine operated initially from 1958 to 1961 and then from 1979 to 1990, producing approx. 16 million tonnes of pyritic tailings. The tailings were deposited in two bed-rock rimmed basins: a north Main Basin and a South Basin, comprising the Panel WMA. The Main Basin is approximately 84 ha in area and the South Basin is approximately 39ha, having a combined watershed drainage area of approximately 280ha. Figure 6 shows the Panel WMA and an aerial view of the site after rehabilitation and decommissioning. The South Basin contains a relatively small quantity of tailings that were deposited during the late 1950s and are contained by two low permeability dams. The majority of the tailings are contained in the Main Basin, bounded within a bedrock basin, and impounded by four engineered, low permeability dams, constructed along about 15% of the perimeter. Drainage from Main Basin enters South Basin via a spillway constructed in a rock rim between the two basins. During the later operating period of the Panel mine/mill and WMA, the tailings in the South Basin were always underwater and the basin was primarily used for holding and storage of the discharge effluent from the WMA for treatment purposes. The effluent treatment plant is located at the south end of the South Basin. The treated effluent is discharged via a series of three hypalon lined sludge settling and polishing ponds to the receiving water system of Quirke Lake.

FIG. 6. Rehabilitated Panel mine/mill and waste management areas, Elliot Lake, Ontario, Canada.

The rehabilitation and decommissioning activities at the Panel WMA started in 1992 and were completed by 1993, submerging the entire basin under a minimum water depth of approximately 1m. To facilitate a single elevation water cover in the Main Basin, excess tailings in its western section that were above the anticipated final water cover elevation were excavated and relocated by trucking to the deeper central and eastern parts of the basin. During site rehabilitation, limestone or lime was incorporated into the exposed and relocated tailings, and hydrated lime slurry was added to the water covers in the two basins to neutralize any resident and historic acidity present, as well as for providing additional alkaline buffering capacity for neutralizing future acid generation within the tailings substrate. The water cover in the WMA is further maintained near neutral conditions by period addition of hydrated lime slurry to the two basins. Because of the large holding capacity available at the Panel WMA, the effluent at this site is only treated seasonally during spring and fall months.

The Panel WMA was extended in 1998–1999 to include a 16 ha Panel Wetland area, located to the east of South Basin in an east-west trending valley, downstream of its main dam. The Panel Wetland area contains partially submerged tailings that were deposited by accidental spillage of tailings in the late 1950s. The tailings in the wetland basin are retained and its water level maintained by an engineered dam at the outlet end to the east.

Stanleigh mine/mill and waste management sites

The Stanleigh mine site and tailings management area are located approximately 5 km northeast of the city of Elliot Lake. The Stanleigh WMA contains tailings from both Stanleigh mine and mill and from a nearby Milliken mine and mill. The Milliken mine and mill operated from 1958 to 1964, producing approximately 5.7 million tonnes of tailings. The

Stanleigh mine and mill originally operated from 1957 to 1960 and then from 1983 until mine closure in the mid 1996.

The WMA has a designed capacity of 71 million tonnes of tailings that would have been produced through the original planned operating period of the Stanleigh mine until 2020. The premature closure of the mine and milling facilities resulted from the cancellation of the long term uranium delivery contracts by the Ontario Hydro utility, the sole purchaser of the mine's uranium production. The total surface area of the WMA is large at 411 ha, consisting of East, West and South Arms, as shown in Figure 7. At closure, the WMA only contained approximately 19.8 million tonnes of tailings, mostly contained within the West and South central arms of the basin.

The Stanleigh WMA is located in several former lake basins where a majority of the tailings were deposited underwater during the latter operating period of the mine. The WMA is bounded by five engineered, low permeability dams. The effluent treatment plant is located on the south-eastern side of the WMA. It is fully automated providing treatment for pH control, dissolved metals and radium removal, flocculation, effluent/sludge filtration and clarification.

FIG. 7. Rehabilitated Stanleigh mine/mill and waste management areas, Elliot Lake, Ontario, Canada.

The rehabilitation and decommissioning activities at the Stanleigh WMA started in 1997 and were completed by 1999 with the completion of the main dam at the south-east end of the basin, upstream of the effluent treatment plant. Tailings deposited in the West Arm section of the WMA during earlier operations of the Stanleigh and Milliken mines that were above the anticipated final water elevation in the basin were excavated and relocated to the deeper central parts of the basin in 1997. Similar to the practice followed at other WMAs, during this relocation period hydrated lime slurry was added to the basin to neutralize resident stored acidity.

Generally because of the underwater disposal of most tailings, the water cover in the Stanleigh WMA was only mildly acidic during the mine operation and thereafter, except in the high elevation areas before tailings relocation and complete submersion. Since completion of the main dam in 1999, the WMA was allowed to fill by natural precipitation and run-off from the combined catchment area of the basin, which took until the fall of 2002 for the water cover to reach the designed operating level. During this period, no effluent was discharged and the treatment plant was idle until October 2002. The Stanleigh WMA is still under a transitional phase, progressing slowly towards the operating equilibrium conditions. The site is currently managed on a monitoring, and care and maintenance basis.

Presently, all mine and WMAs in the Elliot Lake area, including those rehabilitated previously with a vegetation cover are managed for both mining companies by Denison Environmental Services of Elliot Lake.

PERFORMANCE OF DECOMMISSIONED SITES

All WMAs, including the previously decommissioned vegetated and the newly rehabilitated water cover sites are managed in accordance with the facility decommissioning and site management licences. Effluents from all WMAs are collected and treated, on as-and-when required basis, using hydrated lime or any other alkali solution for pH and dissolved metals control, and by addition of a solution of barium chloride ($BaCl_2$) for dissolved radium removal to meet the regulatory discharge water quality standards.

The Stanleigh WMA is located in several former lake basins where a majority of the tailings were deposited underwater during the latter operating period of the mine. The WMA is bounded by five engineered, low permeability dams. The effluent treatment plant is located on the south-eastern side of the WMA. It is fully automated providing treatment for pH control, dissolved metals and radium removal, flocculation, effluent/sludge filtration and clarification.

The water-covered sites are managed additionally by periodic additions of lime slurry to the established water covers to maintain near neutral pH conditions. This practice is followed to provide an in–situ treatment within the water cover for decreasing the treatment and sludge handling loads at the effluent treatment plant.

The performance of the rehabilitated sites was assessed by collecting and analyzing the annual total alkali consumption data, in terms of equivalent limestone requirements per unit area for the integrated basin including the effluent treatment plant, and any additional treatment provided to the vegetated or water cover basins. The performance of the Denison WMA having single elevation water covers, in terms of its annual equivalent limestone requirements/ha, as well as a comparative performance of the vegetated Nordic and water cover Quirke, Denison, Panel and Stanleigh sites are shown in Figure 8.

The results clearly demonstrate the effectiveness of water covers in controlling acid generation. The post decommissioning annual equivalent-limestone-consumption rate/ha at the Denison WMA has decreased to less than 0.03% and 0.15%, respectively of that required during operational and rehabilitation periods. The yearly average equivalent-limestone-consumption rate (1998–2001) for the vegetated Nordic WMA was high at 8.53 tonnes $CaCO_3$/ha/y. The acid generation rate at the Denison, Panel and Stanleigh WMAs has decreased to less than 1.6% of that at the Nordic WMA during the same monitoring period.

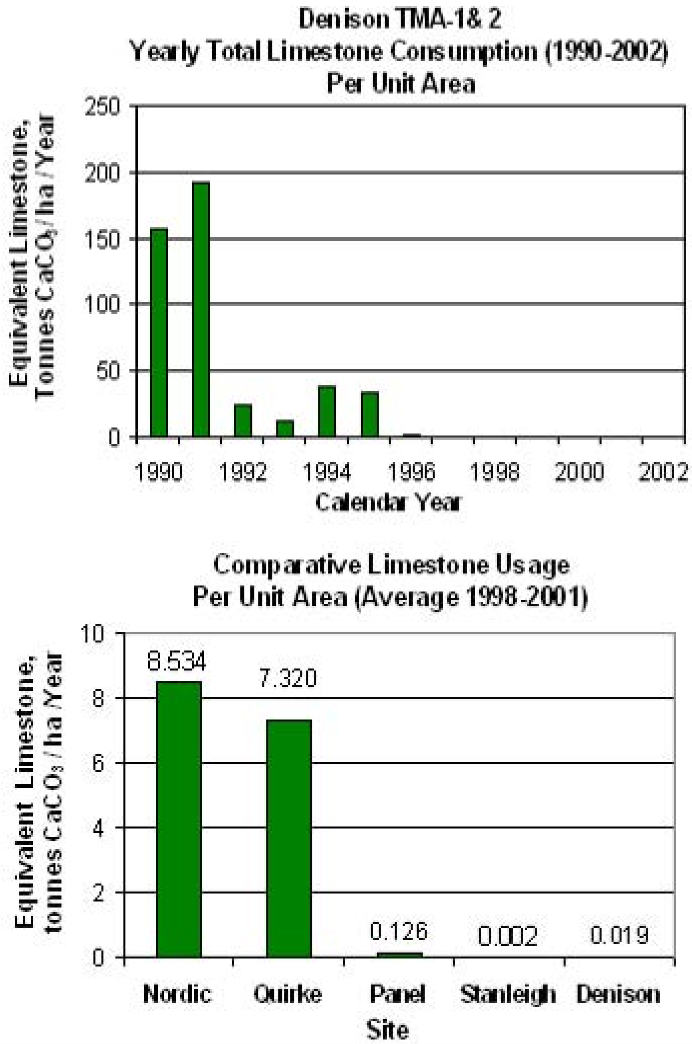

FIG. 8. Performance of water covered and vegetated uranium waste management sites in the Elliot Lake area - annual-equivalent limestone consumption rate per unit area for the various sites.

The post rehabilitation equivalent-limestone-consumption rate for the Quirke WMA was initially high at approximately 7.3 t $CaCO_3$/ha/y during the 1998–2001 monitoring period. It has decreased to ~1.5t $CaCO_3$/ha/y during 2002–2003.[6] Because of its unique hydrological configuration and past exposure history, the Quirke WMA is still flushing out the stored acidity and oxidation reaction products and thus its total alkali requirements are high. With the continued flushing of these products the performance of the Quirke WMA is gradually expected to approach that of Denison, Panel and Stanleigh sites.

URANIUM MINE DECOMMISSIONING - LONG-TERM RADIUM MOBILITY

The decommissioning of uranium mine and waste management sites has been very successful and all primary objectives related to physical and chemical stability of the decommissioned sites have been fully accomplished. Although acid generation in sulfide bearing uranium tailings and waste rock continues to be a cause of environmental concern at most vegetated sites, it has been significantly reduced with the incorporation of water covers at recently decommissioned sites. The mobility of long-lived, uranium-decay-chain radionuclides and particularly that of radium and its progeny, including their parent thorium isotopes, however, would remain the long term and ultimate cause of environmental concern with uranium mine decommissioning. In this respect, the acid mine drainage related aspects are considered to be of a short term duration compared to the long term containment requirements of the naturally occurring radionuclides within the uranium waste management facilities. The leaching and mobility aspects of Ra–226, having a half-life of 1600 y, and as one of the key monitoring parameters associated with uranium mining, both with and without acid generation, are considered below.

In the uranium milling process, according to Constable and Snodgrass [7], most of the radium associated with the uranium ore matrix is first completely dissolved in the hot sulphuric acid leaching process, and then immediately co-precipitated with and/or adsorbed onto the various mineral phases associated with the precipitation of barite ($BaSO_4$), gypsum ($CaSO_4$), oxides/oxy-hydroxides and oxy-sulfates of Fe and Mn, as well as secondary alumino-silicate minerals in the leaching and partial neutralization circuits, and with other metal hydroxides and gypsum in the final neutralization circuit. More than 95% of Ra–226 contained in the uranium ore is immobilized with the tailings solids, leaving a very small fraction in the process solution streams. Because of the fine precipitates, the fine tailings fraction (<75 µm) generally contained higher total radium concentration, as much as twice or more, than the coarse tailings fraction (>75 µm) [7][8][9][10].

Following tailings neutralization and disposal, the residual radium in the tailings porewater is redistributed and decreased gradually as solid-liquid partition equilibrium is established between the two phases at the prevailing pH – Eh (redox) conditions. The sulfate ion concentration in the tailings pore and contact waters, however, controlled the solubility of the sparingly soluble sulfate co-precipitates containing radium, and hence it’s leaching and mobility. The dissolved radium may be further redistributed amongst the Fe-Mn oxide/oxy-hydroxide/oxy-sulfate phases and other adsorption sites in accordance with the shifting partition equilibrium [11].

In the acid generating uranium mine tailings, the immobilized radium is fairly stable during the acid generation phase, and/or during gypsum dissolution, when the sulfate ions so produced controlled the mobility of radium associated with $BaSO_4$ co-precipitate. However, with continued oxidation and eventual depletion of pyrite as well as gypsum, the mobility of radium is enhanced through the increased dissolution of $BaSO_4$ and other secondary sulfate minerals, such as $PbSO_4$ and jarosite ($KFe_3(SO_4)_2(OH)_6(6H_2O)$), in the absence of the sulphate ion solubility control. Constable and Snodgrass [7] observed in laboratory column leaching experiments that under unsaturated leaching conditions up to 80% of total Ra–226 contained in the top 10 cm layer of the experimental tailings was mobilized upon depletion of pyrite. Ra–226 was, however, re-precipitated in the tailings substrate below the zone of pyrite depletion. The authors further suggested that $BaSO_4$ was the main radium mobility-controlling mineral, whose solubility was adversely impacted by the depletion of pyrite and/or other soluble sulfate minerals such as gypsum. While the sulfate control on radium mobility was observed for both pyritic and non-pyritic uranium tailings, it was more pronounced in the former case.

Goulden [8] undertook extensive mineralogical characterization and sequential extraction studies to quantify the association of Ra–226 with the various water soluble, weak acid soluble, cation exchangeable, reducible Fe–Mn oxides/hydroxides and other residual mineral phases in low-sulfide uranium mill tailings from a high grade uranium mine in northern Saskatchewan. The author concluded that while a very low fraction, ~0.35%, of the total Ra–226 contained in the process tailings was associated with the water-soluble mineral components, significantly higher fractions of total Ra–226 at ~54%, ~20% and ~ 15% were associated with ion exchangeable, weak acid soluble and reducible phases of Fe and/or Mn oxides/oxy-hydroxides, respectively. In these cases, both Ra–226 and Ba were extracted concomitantly. A residual 20% of total Ra–226 was associated with the insoluble fraction extractable only in a strongly oxidizing and acidic media. Thus, the mobility of radium may be enhanced in the absence of sulfate ion control due to continued weathering of decommissioned waste management sites, as well as in reducing environments where sulfate reduction may adversely impact the stability of $BaSO_4$ itself.

Laboratory column leaching studies conducted by this author over an extensive seven and a half year study period, simulating both on-land disposal (unsaturated conditions) and shallow water submersion (saturated condition) of pyritic uranium tailings containing ~ 5–7% pyrite, further elucidate the enhanced mobility aspects of Ra–226 in the presence/absence of sulfate ion solubility control as briefly described below. The detailed findings are presented separately in Davé [9][10] and Davé et al. [12].

On-land disposal scenario – unsaturated zone leaching conditions

The unsaturated zone leaching experiments were conducted for two un-oxidized and un-amended uranium tailings: 1) coarse tailings (~96% greater than 75 µm) and 2) un-segregated mill total tailings (~ 50% less than 75 µm). During the acid generation period, the Ra–226 mobility from both of these tailings was extremely low, at approximately <0.20% of total Ra–226 contained in the two tailings, as shown in Figures. 9 and 10, respectively, for the coarse and mill total tailings. However, with continued leaching of the coarse tailings, and upon nearly depletion of pyrite in the top 80% of the tailings height, increased mobility and release of Ra–226 was observed near the end of the study period, when dissolved sulfate ion concentrations in the leachates had decreased to ~100 mg/L (Figure 10). In the mill total tailings, where acid generation continued at a very low rate compared to that of the coarse tailings, no such enhanced release of Ra–226 was noted near the end of the monitoring period.

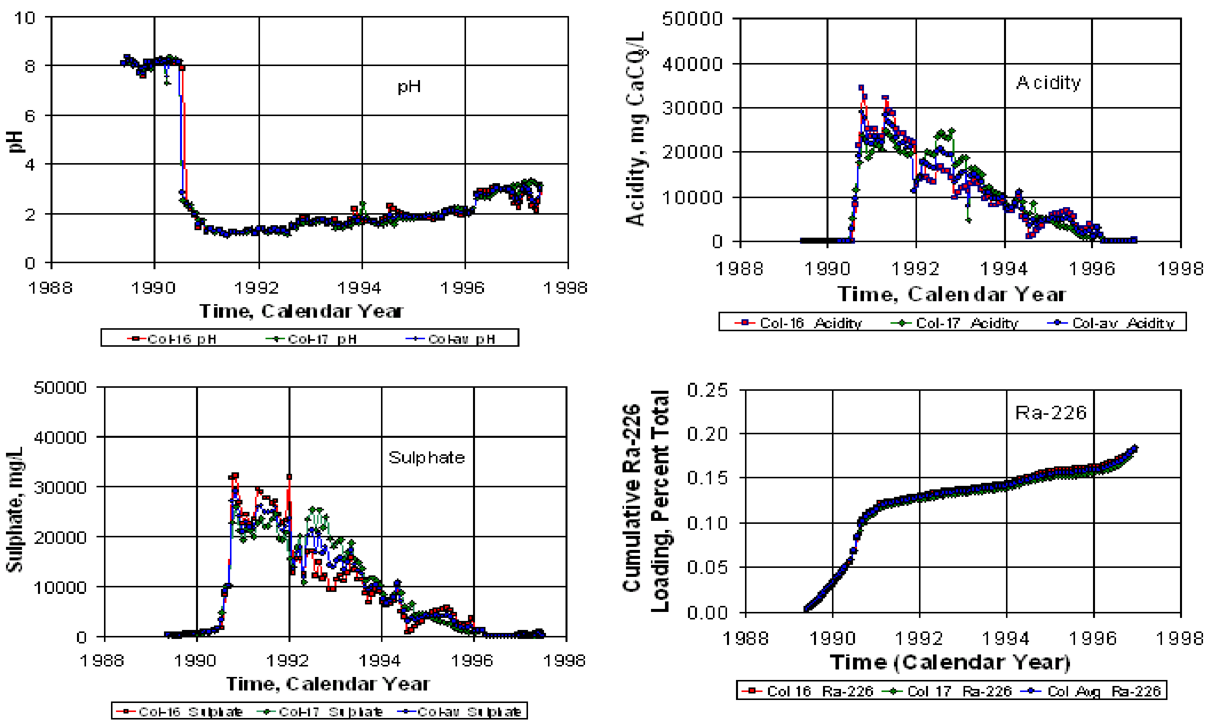

FIG. 9. Unsaturated zone leaching conditions – variations of effluent pH, total acidity, SO_4 and cumulative loading of Ra-226 vs. time for coarse pyritic uranium tailings.

Enhanced release of Ra–226 was also noted, at concentrations as high as ~ 10 Bq/L, during the additional flushing of the above leached coarse tailings under saturated conditions after completion of the leaching study, when the effluent sulfate concentrations were very low at near background levels of < 10 mg/L. The flushing was undertaken by submerging the leached tailings under a shallow water cover using natural lake water to remove all residual oxidation reaction products, which had accumulated during the unsaturated zone leaching of the coarse tailings, at the same time minimizing further oxidation of the remaining un-oxidized tailings. During this flushing process, an additional 1% of the total Ra–226 contained in the coarse tailings was removed by approximately 35 pore volume exchanges over a two and a half month's period. The total Ra–226 removal in this process was about five times that of the seven and a half year unsaturated zone leaching study. With further leaching of the coarse tailings under unsaturated conditions, after flushing and removal of the oxidation reaction products, the mobility of Ra–226 decreased again due to acid generation and increased sulfate ion concentration.

In both of these unsaturated zone leaching cases, the total amount of Ra–226 mobilized during the acid generation phase was significantly low and controlled by sulfate ion production/release.

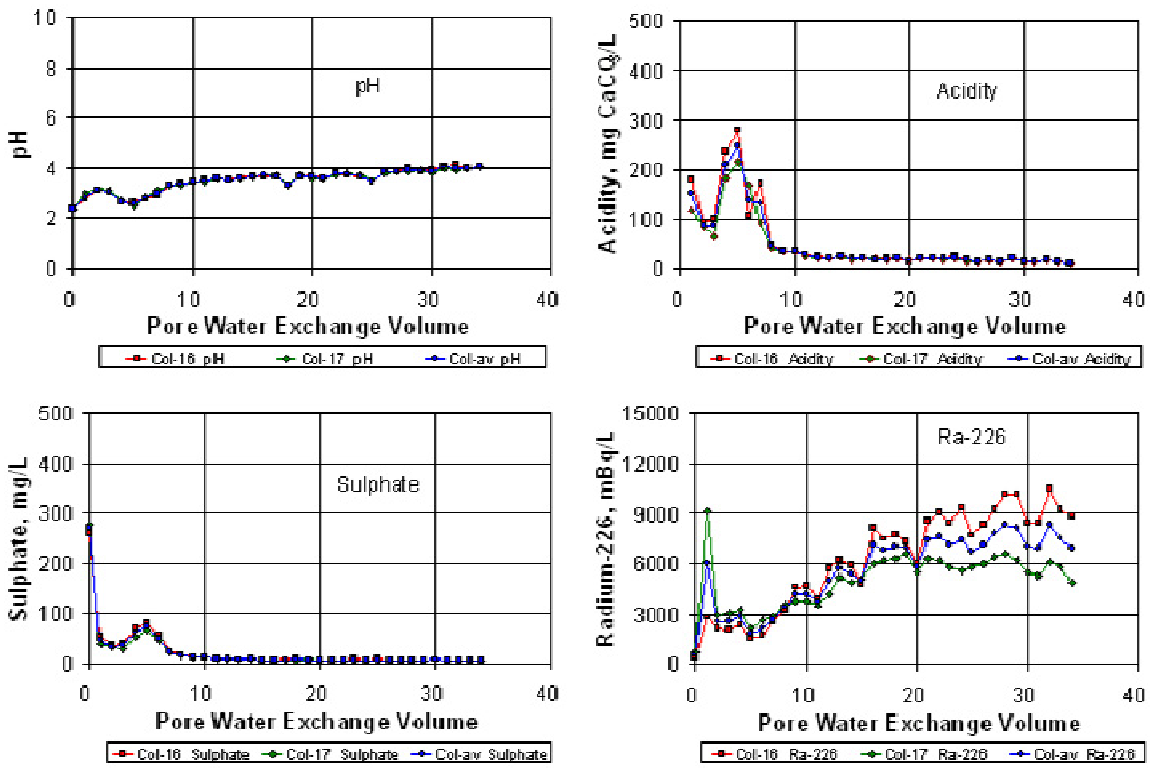

FIG. 10. Unsaturated zone leaching conditions – variations of effluent pH, total acidity, SO_4 and cumulative loading of Ra–226 vs. time for mill total uranium tailings.

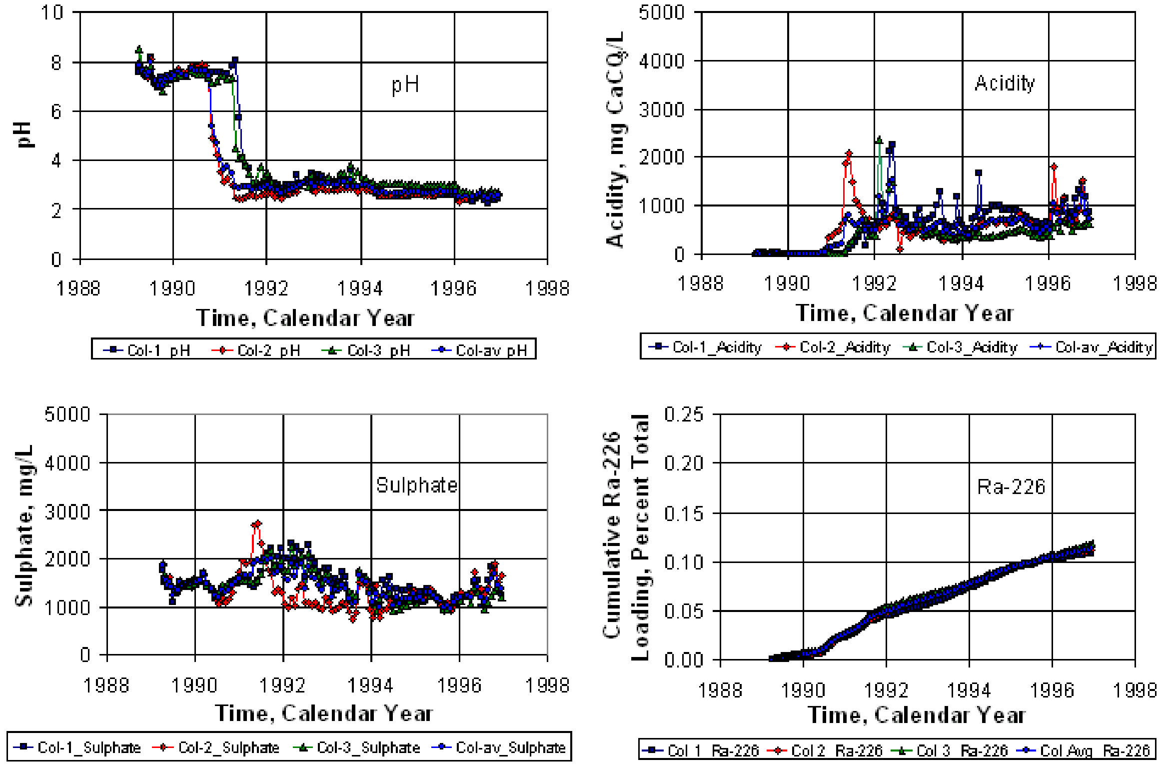

FIG. 11. Post leaching, saturated zone flushing of coarse pyritic uranium tailings – variations of effluent pH, total acidity, SO_4 and cumulative loading of Ra–226 vs. time.

Underwater disposal scenario – saturated zone leaching conditions

The saturated zone leaching experiments were conducted using un-oxidized, coarse pyritic uranium tailings, submerged under shallow water cover conditions to minimize their surface oxidation to a low rate controlled by the availability of dissolved oxygen in the water cover. Separate experiments were undertaken for tailings containing gypsum, and for tailings depleted of gypsum for surface water quality monitoring for a period of approximately fifteen months, and for tailings, both before and after gypsum removal, for long term porewater quality monitoring for a period of seven and a half years. The first two experiments were conducted using aquarium type lysimeters and natural lake water, and the later one using column lysimeters and de-ionized water to facilitate the long term porewater drainage requirements.

For the submerged coarse pyritic uranium tailings under shallow water conditions, significant mobilization and release of Ra–226 was observed both in the surface water cover as well as in the porewater drainage after complete depletion of gypsum, as shown in Figures 12 and 13 for surface and pore water quality profiles, respectively. The dissolved Ra–226 concentrations in the surface water cover of the gypsum-depleted tailings increased significantly to 33 Bq/L during the initial period of low dissolved sulfate concentrations, and decreased gradually to ~6 Bq/L with increasing sulfate concentration in the water cover (Figure 12).

For the porewater drainage study under shallow water cover conditions, the mobility and cumulative release of Ra–226 was significantly high at ~ 8% of the total Ra–226 contained in the coarse tailings, compared to ~ 0.2% for the unsaturated zone leaching of the same tailings during the seven and a half year leaching period. The enhanced release of Ra–226 in the porewater drainage was concomitant with the breakthrough and increased drainage of dissolved iron in the porewater [12]. Martin et al. [13] also observed a significantly increased mobility of Ra–226 in the surface water cover as well in the shallow zone porewater of decommissioned pyritic uranium tailings in both coarse and fine tailings areas. The authors attributed the increased release of Ra–226 in the fine tailings areas to the microbial reduction of (Ra)$BaSO_4$ co-precipitate upon depletion of the sulfate ion solubility control in zones where a dense vegetation cover on the submerged tailings had contributed to anoxia, resulting in vegetative reduction of sulfate just below the benthic boundary.

Collectively, these results show that the increased mobility and release of Ra–226 may be a cause of long term environmental concern at both on-land and underwater deposited uranium tailings when sulfate ion mobility control has been exhausted. Additionally, these findings may have implications on the long term radiological stability of the effluent treatment sludge itself, containing (Ra)$BaSO_4$ precipitates along with those of gypsum and other metal hydroxides. While the sludge is stable during on-going treatment operations and as long as the sulfate ion solubility control is present, the loss of the latter under both oxic and anoxic substrate conditions, combined with microbial degradation of sulfate in reducing environments, has the potential to re-dissolve the immobilized radium. Because of the long term stability aspects of the effluent treatment sludge, the decommissioned uranium mines in the eastern Germany cast the dewatered sludge in a concrete matrix and dispose the cast slabs at a suitable sub-terrain location.

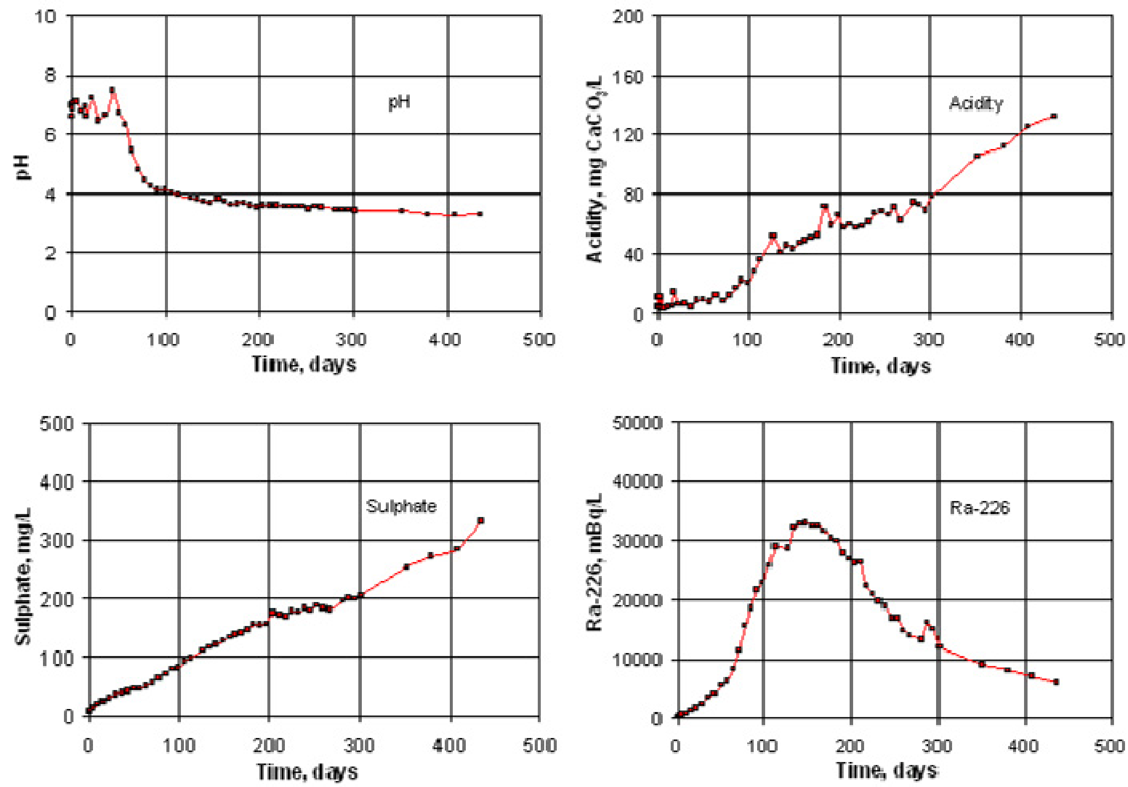

FIG.12. Variations of pH, total acidity, sulfate and Ra–226 concentrations in the surface water cover vs. time for the submerged coarse pyritic uranium tailings.

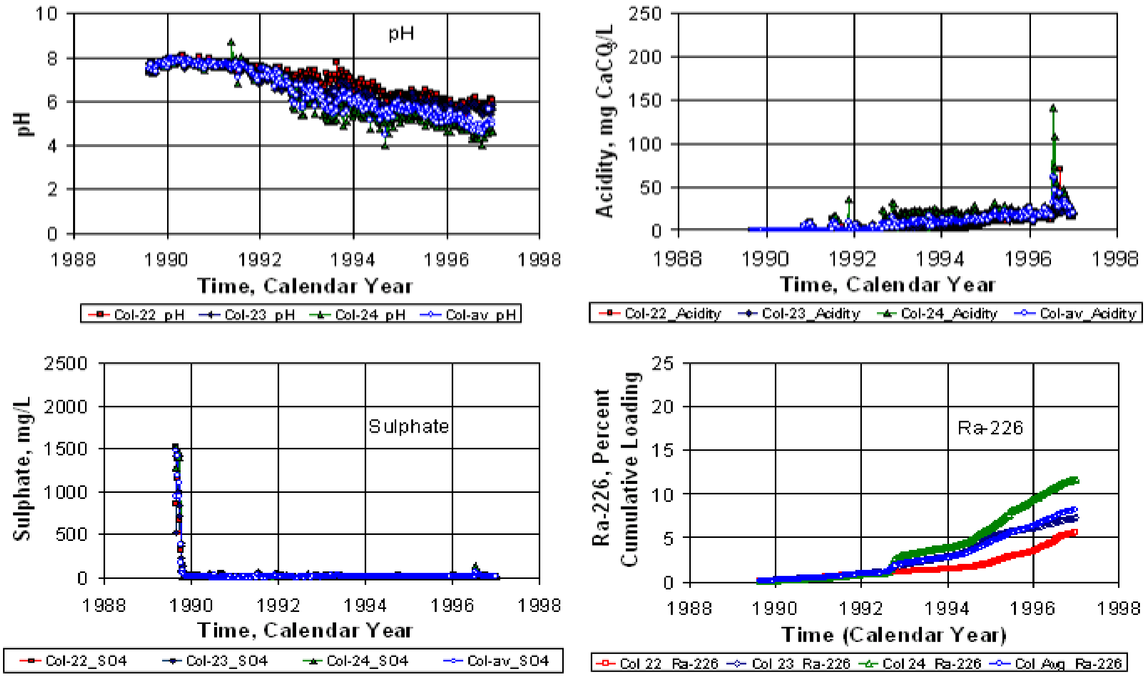

FIG. 13. Variations of pH, total acidity, sulfate conc. and cumulative Ra–226 loadings vs. time in the porewater drainage for the submerged coarse pyritic uranium tailings.

It should, however, be emphasized that the sulfate solubility related control aspects apply only to the fraction of total radium that has been immobilized with the insoluble metal or other sulfates. Radium is also strongly attached to Fe-Mn oxy-hydroxides minerals, which are common to most uranium tailings and treatment sludge, and may play a key role in controlling the additional mobility of radium under both oxic and anoxic environmental conditions [11]. The existing database on radium mobility, however, is still very limited to fully quantify the long term radiological stability aspects of decommissioned uranium mine tailings, waste rock and effluent treatment sludge. Thus, further investigations in this area are warranted.

SUMMARY AND CONCLUSIONS

The rehabilitation and decommissioning of inactive uranium mine/mill and waste management sites in Canada have been very successful through the joint efforts of the mining industry, government and regulatory authorities. A majority of the past historic mine sites have been rehabilitated and managed under the current regulatory framework for such sites. Efforts are underway to develop decommissioning and management strategies for the remaining inactive and abandoned sites. All newer close-out mines in the Elliot Lake area, where acid mine drainage is a major issue of environmental concern, are decommissioned with engineered waste management facilities to provide a shallow, in situ water cover having a minimum depth of ~1 m above the submerged waste. The water cover has reduced the acid generation at these sites to a low rate, and has minimized the exhalation of radon gas and its progeny from underwater deposited wastes. During active treatment and transition phases, all sites are regularly monitored and are on care and maintenance basis to meet regulatory requirements. Effluents at these sites would continue to be collected and treated until required. During the acid generation phase, the mobility of Ra–226 was low. It was, however, enhanced upon depletion of the sulfate ion solubility control for both on-land and underwater disposal scenarios of pyritic uranium tailings. This may be a cause of long term environmental concern and further investigations in this area are warranted.

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HISTORY AND PRESENT STATE OF URANIUM MINING IN THE CZECH REPUBLIC

B.Michálek
DIAMO state enterprise, GEAM branch plant, Dolní Rožínka, Czech Republic

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Abstract

From 1945 to the mid 90s of the last century, uranium mining was a major industry in the Czech Republic, which was at the forefront of uranium concentrate production in the world (see Figure 1). However, since the end of the 1980s, production of uranium ore has gradually diminished. This has been because of the depletion of some deposits and especially due to a marked reduction in sales opportunities as a result of the economic-political changes taking place at the turn of the 90s of the last century. At present, the Rožná deposit is the only uranium deposit being exploited in the Czech Republic.

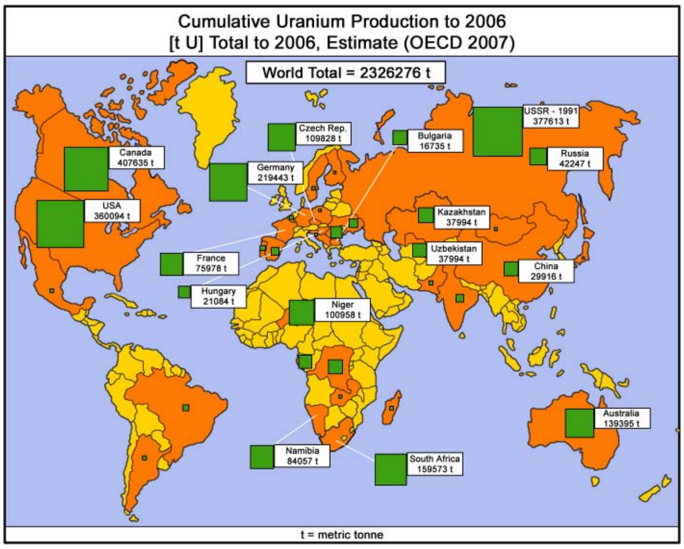

FIG. 1. Total world production of uranium 1945–2006 (source WISE Uranium Project).

Uranium mining was thus designed to solve, in a relatively short time, problems connected with the progressive phasing out of mining and principally with closing and decommissioning underground uranium mines, without having at that time virtually any relevant experience. The situation was made still worse by the fact that deposits being mined were of various genetic types, operations were done under complicated mining-geological, hydrogeological and other natural conditions, and deposits were situated at various depths (even more than 1000 m below the surface). Thus a single, uniform method of mine closure could not be employed; instead each of the deposits required a tailor-made approach and the application of specific procedures. The minimization of negative impacts on the surrounding environment and human health from the release of radionuclides and other hazardous pollutants that form part of the mineral sequence in particular ore districts, both during the mining of the deposit and subsequently during the closure of the mine and removal of mining impacts, is the first and foremost objective of uranium mining.

CHARACTERISTICS OF URANIUM DEPOSITS IN THE CZECH REPUBLIC

Uranium deposits in the Czech Republic (Figure 2) are situated in a geological system broader than that represented by the Czech Republic's territory, namely in the Bohemian Massif, which is the denudation remnant of the Variscan mountains. Here we find endogenous and exogenous deposits formed by uranium mineralization; the endogenous deposits are confined predominantly to crystalline series and granitoid masses and the younger exogenous deposits to platform formations of the Permian-Carboniferous, Cretaceous and Tertiary.

The endogenous deposits are deposits in the areas of Příbram, West Moravia, West Bohemia, Jáchymov and Horní Slavkov. From the point of view of geological structure, morphology of ore bodies and the deposit accumulations of ores, they represent a case of three genetically different types (hydrothermal deposits):

(1) deposits in tectonic zones and veins of crystalline rocks of the Bohemian Massif (Rožná, Olší, Zadní Chodov),
(2) veins in the rocks of the geosynclinal structural level confined to large granitoid masses (Příbram, Jáchymov, Horní Slavkov),
(3) tectonical zones and veins in the Variscan granitoids (deposit of Vítkov in the area of West Bohemia).

The exogenous deposits occur in Cretaceous sediments represented by sandstones and siltstones in places of uranium mineralization. These are almost flat-lying ore bodies of the polygenous nature (infiltration and hydrothermal) that have large thicknesses. Stráž pod Ralskem and Hamr are examples of such deposits exploited in the Czech Republic.

With regards to the types of deposits (based on systems of development and mining), the following two types of industrially utilised deposits are important:

(1) ore bodies (deposits) of the zonal, vein and metasomatical types, strongly inclined in solid rocks and having mineralization thicknesses ranging predominantly from 1.5 to 2 m, less often of up to 10 m,
(2) ore bodies (deposits) of the large thickness (10–20 m) almost flat-lying in sandstones and siltstones.

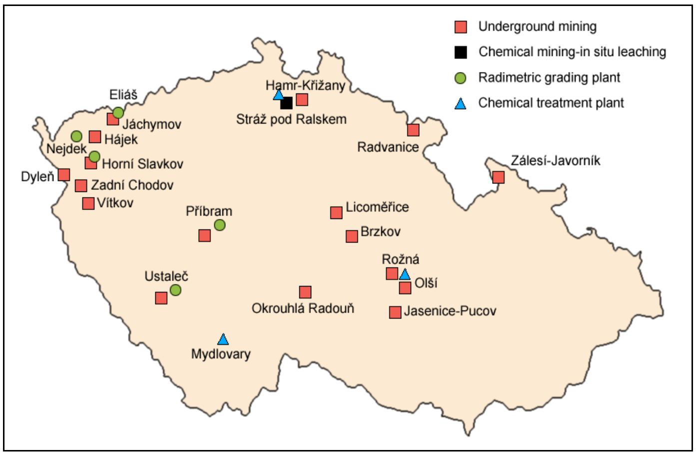

FIG. 2. Major localities of uranium mining and treatment.

SYSTEM OF DEVELOPMENT AND MINING OF URANIUM DEPOSITS IN THE CZECH REPUBLIC

Deposits situated in highly dipping veins, zones and metasomatical bodies in solid rocks were developed by vertical shafts and main crosscuts leading from them at a vertical spacing of 50 to 80m. The next exploration and simultaneously detailed development were performed through crosscuts parallel to the strike and drifts. Raises, through which particular blocks were prepared, were driven from drifts and headings. Mining in horizontal slices at a height of 2.5-3.0m was executed using the following mining methods:

- overhand stoping with backfilling the worked-out voids with local backfilling material, less frequently materials from other places;
- selective mining with leaving pillars;
- shrinkage stoping;
- underhand slicing with artificial roof caving;
- in metasomatical ore bodies in the deposit of Vítkov, the method of cross-open chambering was also used.

The depth of mining usually reached up to 600–700 m below the surface. At extremely great depths, the deposits of Zadní Chodov (1250 m), Příbram (1550 m) and Rožná (1100 m) were exploited.

The exogenous deposit of Hamr, formed by large ore bodies in sandstones and siltstones, was mined by employing the room and pillar method (room length of up to 150 m, room width of 4–5 m) and, to a small extent, by longwalling and shortwalling. With reference to the fact that in these deposits it was necessary to protect the surface and especially the water-bearing Turonian horizon in beds overlying the ore bodies (representing the largest water reservoir in the Czech Republic), the worked out voids were backfilled with consolidated backfilling material of strengths ranging from 4 to 10 MPa. The deposit occurs at a depth of about 250 m and was developed by vertical shafts. Development crosscuts were, in the majority of cases, driven below the ore bodies (15–30 m pillar). Raises for removing the material were driven directly in the ore bodies from these crosscuts into the relevant development drifts.

The deposit of Stráž pod Ralskem was exploited by acidic leaching the uranium ore from boreholes directly in the ore bodies (in situ leaching). Mining in Cenomanian sandstones in an area of 6.3 km^2 was performed by 9300 boreholes from the surface to a depth of more than 200 m. The leaching agent was a mixture of acids, H_2SO_4 (3.7 mil.t was used), HNO_3 (0.27 mil.t), HCl (0.025 mil.t) and NH_3 (0.1 mil.t). The removal of acid leaching solutions by pumping from the rock environment has been carried out since 1996 and will continue for decades.

AN OVERVIEW OF EXPLOITATION IN PARTICULAR DEPOSITS

Since 1945, altogether about 109 000 t of uranium has been mined in the Czech Republic. Six major mining areas contributed to this output; a small amount was also mined as part of geological exploration in other regions (see Table 1). The duration of mining in individual areas and the proportions of these areas in the total production are presented in Table 1 and the total production of uranium for the years 1945–2006 is then given in Figure 3. The uranium industry represented an important employer in that period; the maximum number of people employed amounted to 48 000 in 1953, in the 1970s and 1980s the number of employees ranged from 30 000 to 33 000, including all auxiliary activities (geological exploration, construction of machines, research and development institutes and others).

TABLE 1. OVERVIEW OF EXPLOITATION IN PARTICULAR URANIUM DEPOSITS

Mining area	Uranium deposit	Exploitation duration	Production
			% of total CR production
Příbram	Příbram	1949 - 1992	36.5
West Moravia	Rožná, Olší-Drahonín, Zálesí, Javorník, Chotěboř, Slavkovice-Petrovice, Radvanice	1957 - to present (Rožná),	19.2
North Bohemia	Hamr	1974 - 1993	10.3
	Stráž pod Ralskem (leaching in situ)	1969 - 1996, since 1996 uranium acquired by chemical leaching as part of remediation	15.1
West Bohemia	Zadní Chodov, Vítkov, Dyleň, Okrouhlá Radouň, Hájek, Ruprechtov	1954 - 1992	9.0
Jáchymov	Jáchymov	1947 - 1962	6.2
Horní Slavkov	Horní Slavkov	1949 - 1963	2.2
Geological exploration	Jasenice-Pucov, Brzkov, Licoměřice, Ustaleč	1955 - 1990	1.5

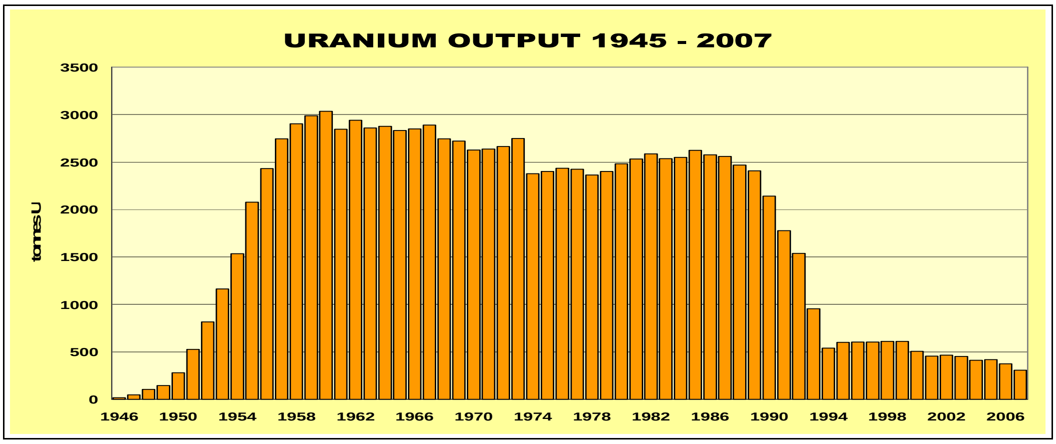

FIG. 3. Uranium production in the Czech Republic in the period 1945–2007.

MINE DECOMMISSIONING AND THE MITIGATION OF CONSEQUENCES OF URANIUM ORE MINING AND TREATMENT

The decommissioning of underground uranium mines and the mitigation of the consequences of mining and treatment consists in the decommissioning and securing of mine workings or empty voids after underground exploitation; in the creation of a new mine water regime; the removal of or finding new uses for surface structures; the reclamation of waste heaps, subsidence troughs and subsidence sinkholes, and primarily the restoration and reclamation of tailings ponds of chemical treatment plants. One wholly specific problem is restoration related to chemical mining in the deposit of Stráž pod Ralskem, where chemical mining was finished in the year 1996. The removal of acid solutions from underground aquifers and the restoration of the rock environment will continue for decades.

The aforementioned activities are ensured by the state enterprise DIAMO, or its branch plants. As for the sequence of operations or individual actions, the Ministry of Industry and Trade has approved priorities that consider, on the one hand, the topicality of works from the point of view of possible hazard to the environment and health of the population surrounding individual localities, and on the other hand, the realistic possibilities of the national budget from which all these works are funded. The highest priority is given to activities connected with the use of contaminated waters and the securing of tailings ponds, followed by the decommissioning of main mine workings, or other mine voids endangering the surface by their negative effects.

The decommissioning of uranium mines, treatment plants, tailings ponds, and the mitigation of all consequences of mining activity represents a technically complicated as well as time and money-consuming process. In addition to resolving mining problems themselves, it is necessary, in the course of decommissioning and restoration works, to deal with problems of uranium mining, i.e. to work with the sources of ionising radiation and the protection of the environment and population against potential emissions of radionuclides. That is why even at the stage of decommissioning and restoration, the constant monitoring of the working environment as well as of workers, and the environment more generally (i.e. the outlets and the surroundings of individual localities), is ensured; and these activities are subject to the supervision of the State Office for Nuclear Safety.

In localities, where the used method of decommissioning and reclamation does not meet present requirements concerning the securing of safety and primarily environmental protection (i.e. localities where uranium mining and treatment were brought to an end in the 1960s), measures to remedy the present state are being gradually implemented.

PRESENT STATE OF SELECTED LOCALITIES WITH FINISHED MINING OPERATIONS

When exploitation was finished in the mines and pumping systems were shut down, the process of spontaneous mine flooding started. Depending on the amount excavated, the depression basin area and the hydrogeological conditions of the deposit, this process took several years. During this time, conditions for proper mine water management in the “collection – controlled draining from underground spaces – purification – discharge” mode had to be created in advance. Only this ensures that shallow underground and surface water is not threatened by uncontrolled leakage of contaminated water from the flooded mine in future.

The liquidation of mines on the vein, zone and metasomatic deposit types consisted primarily in filling the main mine outlets on the ground level, the so-called main shafts. Raises and mining areas coming up to ground level were also filled. The geological and hydrogeological situation of these locations, mining methods used, and in many cases, the considerable underground mining depth did not require backfilling other mining works or other free underground spaces in connection with their liquidation. Unconsolidated backfill was used to fill the shafts, raises and near-surface stopes; untreated material from mine dumps created during excavation was used as backfill material. Much more difficult was the liquidation of mines on the Hamr deposit and the in situ leaching operation on the Stráž pod Ralskem deposit (endogenous deposits). This is not the subject of this paper, however.

It is the following major uranium deposits where exploitation has finished:

Příbram deposit

Present state: the mines have been decommissioned and underground spaces flooded. Since 2005, the mine water purification plant at shaft No. 19 has been in operation. Designated mine dumps are processed into crushed aggregate and sludge is deposited in the sludge lagoon. Usable buildings and mine premises are being prepared for sale or gradual demolition and the area for remediation. Mine waters: leaching, draining, excess water from the sludge lagoon and rinse water from the mine dumps are discharged into the deposit. Contaminated mine waters from the deposit are pumped by shaft No. 19 to the mine water purification plant and discharged to a surface watercourse. The volume of mine water accumulated underground is about $20.0 \cdot 10^6$ m^3.

TABLE 2. MINE WATERS FROM THE PŘÍBRAM DEPOSIT

Water type	Discharged water volume	Main and secondary contaminants	
Mine waters from deposit	1104000 $m^3.year^{-1}$	pH = 7.17 – 8.0	SO_4^{2-}, Zn, As, Cu, Cl^-
		U = 7.05 – 8.9 $mg.l^{-1}$	
		^{226}Ra = 1.02 – 1.37 $Bq.l^{-1}$	
		Fe = 8.0 – 19.9 $mg.l^{-1}$	

Vítkov deposit

Present state: the mine has been decommissioned, underground spaces have been flooded, the mine waste dump was removed (treated to crushed aggregate) and the surface area reclaimed. Remaining buildings are being prepared for sale or demolition. Mine waters: after flooding the mine, there was a tiny outflow of non-purified mine waters in the field into the Mže River, but without environmental risk. Long term monitoring of waters is being carried out. The volume of accumulated mine waters in underground spaces is about $2.5 \cdot 10^6$ m^3.

TABLE 3. MINE WATERS FROM THE VÍTKOV DEPOSIT

Water type	Discharged water volume	Main and secondary contaminants	
Mine waters from deposit	24660 $m^3.year^{-1}$	pH = 6.5 – 7.5	SO_4^{2-}, Cl^-, Fe
		U = 0.03 – 2.00 $mg.l^{-1}$	
		^{226}Ra = 0.02 – 3.20 $Bq.l^{-1}$	

Zadní Chodov deposit

Present state: the mine has been decommissioned, underground spaces have been flooded and the surface area has been partially reclaimed. Mine dumps were sold and treated into crushed aggregate. Usable buildings are being prepared for sale or demolition. Mine waters: outflow of contaminated mine waters in the field after flooding the mine: discharge into a surface watercourse. Controlled pumping and purification of out-flowing waters and long term monitoring are being carried out. A mine water purification plant is in operation with the prospect of being shut down owing to gradually stabilizing water chemistry. The volume of accumulated mine waters in underground spaces is about $3.1 \cdot 10^6$ m^3.

TABLE 4. MINE WATERS FROM THE ZADNÍ CHODOV DEPOSIT

Water type	Discharged water volume	Main and secondary contaminants	
Mine waters from deposit	509600 $m^3.year^{-1}$	pH = 7.0 – 7.8	SO_4^{2-}, Cl^-, Fe
		U = 2.5 – 6.0 $mg.l^{-1}$	
		^{226}Ra = 0.07 – 1.70 $Bq.l^{-1}$	

Okrouhlá Radouň deposit

Present state: The mine has been decommissioned, underground spaces have been flooded, and the surface area reclaimed. Usable buildings and premises of the mine have been sold. Mine waters: The mine water level is maintained by pumping to prevent any uncontrolled overflow into the surrounding environment. Purified waters are discharged into a surface watercourse. Long term monitoring is being performed. A mine water purification plant is in operation with the prospect of being shut down owing to gradually stabilizing water chemistry. The volume of accumulated mine waters in underground spaces is about $1.2 \cdot 10^6$ m^3.

TABLE 5. MINE WATERS FROM THE OKROUHLÁ RADOUŇ DEPOSIT

Water type	Discharged water volume	Main and secondary contaminants	
Mine waters from deposit	74000 $m^3.year^{-1}$	pH = 7.1 – 7.2	SO_4^{2-}, Cl^-, Fe
		U = 5.0 – 11.0 $mg.l^{-1}$	
		^{226}Ra = 1.0 – 14.0 $Bq.l^{-1}$	

Olší–Drahonín deposit

Present state: The mine has been decommissioned, underground spaces have been flooded, the surface area reclaimed and buildings and premises of the mine have been demolished. Mine waters: The mine water level is maintained by pumping to prevent any uncontrolled overflow into the surrounding environment. A mine water purification plant is in operation. Purified waters are discharged into a surface watercourse. Long term monitoring is performed. The volume of accumulated mine waters in underground spaces is about $2.2 \cdot 10^6$ m^3.

TABLE 6. MINE WATERS FROM THE OLŠÍ – DRAHONÍN DEPOSIT

Water type	Discharged water volume	Main and secondary contaminants	
Mine waters from deposit	210000 $m^3.year^{-1}$	pH = 6.1 – 7.5	SO_4^{2-}, Fe, NO^{3-}
		U = 5.5 – 13.0 $mg.l^{-1}$	
		^{226}Ra = 0.1 – 2.7 $Bq.l^{-1}$	

ENVIRONMENT PROTECTION FROM THE INFLUENCE OF URANIUM MINING

Uranium mining, which comes knowingly and deliberately into contact with natural sources of ionising radiation, must resolve specific problems associated with the possible release of radiation sources into the environment. From this point of view, it is necessary to pay the greatest attention to mine waters dissolving uranium and radium, and thus representing a medium of transport for radionuclides. That is why the proper management of mine waters in the regime “collection – controlled draining from underground spaces – purification – discharge” is necessary both in the course of deposit exploitation and in the phase of mining operation cessation, because only in this way will shallow groundwater and surface waters not be endangered by any non-controlled leak of contaminated mine water from the deposit.

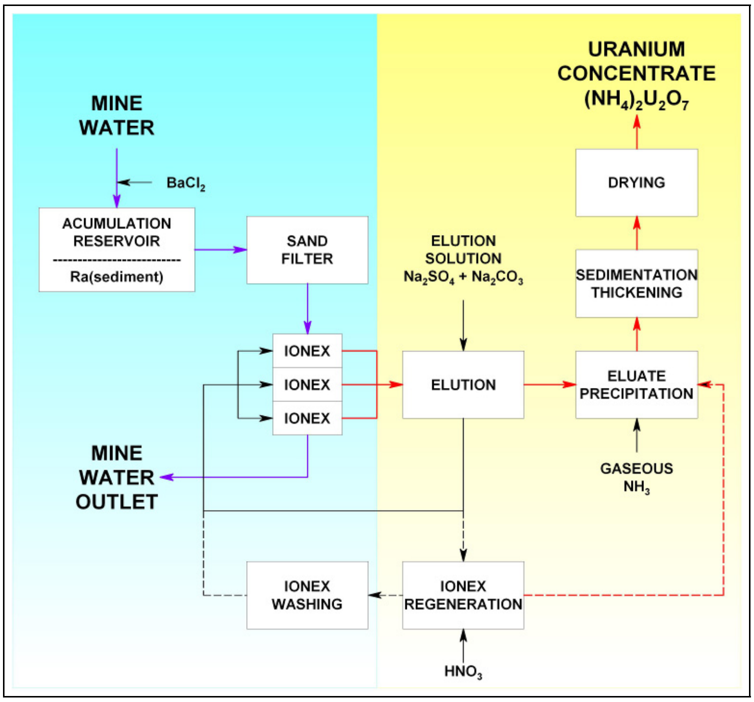

FIG. 4. Block diagram of mine water purification by sorption of uranium in ion exchangers.

To purify mine water, two possible technologies are applied in principle. The basic technology is based on the retention of uranium in ion exchange resin (ionex, e.g. Varion ionex type) at the simultaneous precipitation of radium contained in the water (diagram in Figure 4). This technology for mine water purification makes it possible to obtain uranium or uranium concentrates from waters as an accompanying effect of water purification even long after the finish of the classical exploitation of the deposit (see example of the deposit of Olší, Figure 5). Besides the chemicals presented in the diagram (HNO_3) or the solution of sodium chloride and sodium carbonate (NaCl and Na_2CO_3 at the ratio of 10:1) a solution of nitric acid can also be used as an elution solution. In this case, the precipitation of eluate is carried out by sodium hydroxide (NaOH), and the obtained uranium concentrate is chemically sodium diuranate ($Na_2U_2O_7$). In individual localities with completed mining operations, the duration of the process of mine water purification is expected to last more than 30 to 40 years until the values of concentrations of dissolved substances in the subsurface water of flooded mines probably achieve values admissible for the direct discharge of this water.

The technology of precipitation of water-soluble uranium together with other elements (Ra, Fe, Mn, and others) by calcium hydroxide and the deposition of a dried precipitate on a secure landfill is applied to those deposits with completed mining operations, where the content of uranium in waters is not significant (less than 0.5 $mg \cdot l^{-1}$), but exceeds the limits for the contents of dissolved substances determined for the discharge of mine waters into watercourses.

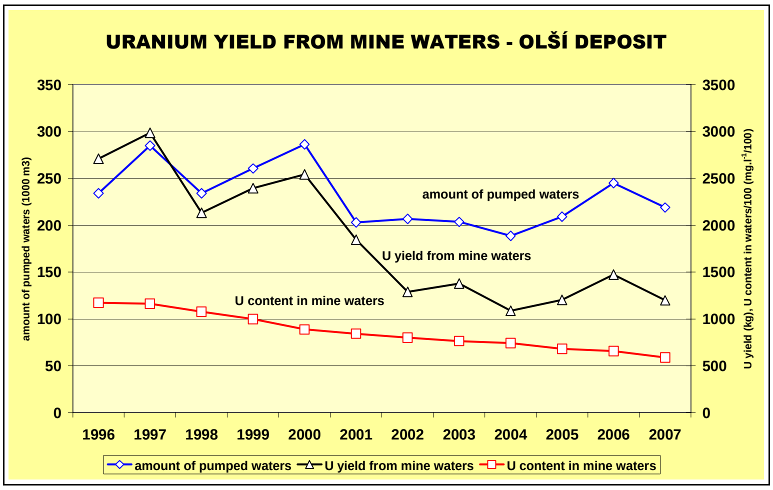

FIG. 5. Yield of uranium at the purification of mine waters drained from the flooded Olší – Drahonín deposit.

As a by-product of the purification of mine waters drained from closed and flooded uranium mines, about 20 t of uranium is acquired in the Czech Republic annually. To complete the picture, it is necessary to mention the process for remediating the rock environment in the deposit of Stráž pod Ralskem, where at present about 50 t of uranium per year is acquired as a by-product in this process. As remediation progresses however, the yield of uranium diminishes.

CONTINUATION OF URANIUM MINING IN THE CZECH REPUBLIC

A turning point occurred in the market for natural uranium in the year 2004, which was caused by a growth in demand and manifested itself in a rapid and sharp increase in the price of this commodity. In view of the persistent discrepancy between the available amount of uranium for sale and the reactor requirements in the world, one can assume that the uranium price will stabilize at a sufficiently high level in the near future, which will further enable the effective mining and production of uranium in the Czech Republic. With reference to the expected economic conditions of mining, the level of uranium ore reserves in the Rožná deposit, and certain prognoses for future possible development in ore mineralization, it is realistic to continue exploiting this deposit. In addition, other deposits having verified reserves of uranium ores, which could be mined under certain conditions, also exist in the Czech Republic.

According to the Decree of the Government of the Czech Republic No. 1316/2005, mining operations were to finish in the Rožná deposit in 2008; the reason being the working out of balance (economic) reserves of uranium ore to a depth of 1100m below the surface. Although reserves have been verified even below this level, the mining of them was not considered a possibility. The deposit was put into operation in 1957, and since then exploitation has been continuous. The general advance of mining is from top to bottom. This means that at first, subsurface parts of the deposit were extracted (uranium mineralization was found already at a depth of 2.0–2.5 metres below the surface). Gradually mining operations proceeded to increasing depths, and at present most works are done at depths ranging from 950 to 1100 metres below the surface. The deposit is developed to a depth of 1200 metres (24^{th} level). From the beginning of exploitation up to 2007, altogether 15 897 million tonnes of ore with an average U grade of 0.117 kg per tonne of ore were produced, which represents 18 636 t of uranium.

The continuation of uranium mining from the deposit of Rožná (Figure 6) is now planned, in accord with the new government decree No. 565 from 23 May 2007, to a final depth of 1200 m, i.e. the 24th level, and concerns economically extractable reserves. Below the level of 1200 m, geological exploration work will be performed to verify new reserves. The plan for mining the deposit of Rožná after the year 2008 requires that the development of the 23rd level be completed and the redevelopment of mine workings on the 24th level, which were abandoned in connection with the phasing out of mining at the beginning of the 1990s. With regard to the extent of works, it seams feasible to start mining operations on the 24th level in mid 2009 and on the 23rd level at the end of 2009. For this period, the amount of reserves prepared for mining to the 22nd level is sufficient. Based on the distribution of uranium ore reserves and at the expected certain increment, it is possible to extract annually 200–220 t of uranium in the next few years.

A prognostic appraisal is carried out on the basis of the expected development of clusters of ore bodies in deep levels of the deposit. Of these, the largest ore bodies are confined to zones 1 and 1Z on the boundary of the mining claim, and these ore bodies have not any continuity on higher levels. The prognostic appraisal of the deposit as far as reserves below the 24th level are concerned can be made for three levels, i.e. vertically in the range of 150 m; total reserves in the interval from the 24th to 27th level can be expected to be about 350 t of uranium. From the point of view of assessing any future utilization of the deposit it is thus necessary to conduct geological-exploration works. The first step in the verification of reserves below the 24th level is performing a drill-hole exploration from the 24th level. However, this is conditional upon making mine workings on the 24th level accessible and by driving level development gates and chambers, from which holes will be drilled into the area of expected ore mineralization below the 24th level. Works on the realization of this phase were commenced in 2007 and partial results of exploration will be known at the end of 2008.

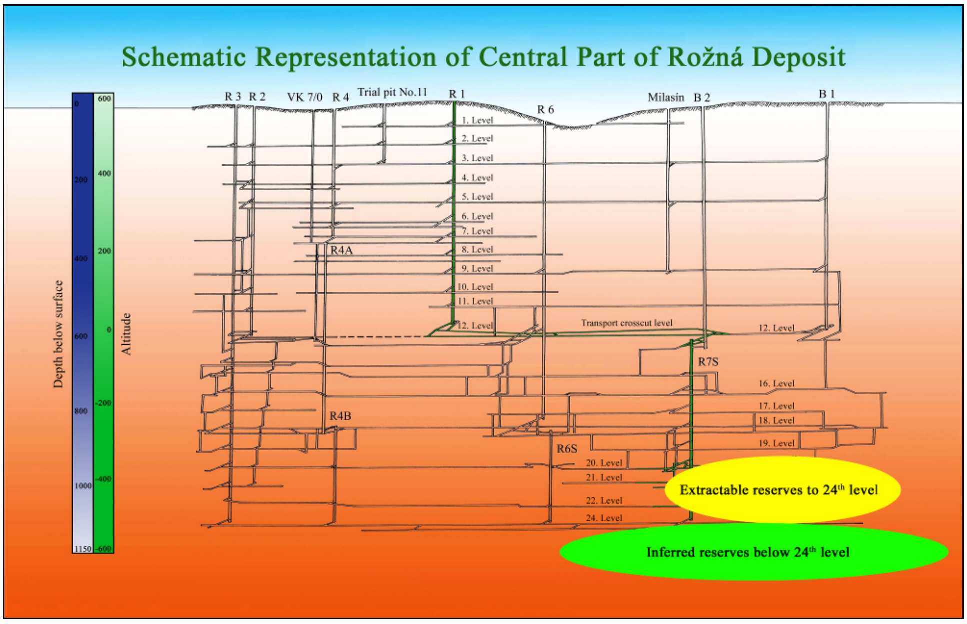

FIG. 6. Layout of current uranium reserves in the Rožná deposit.

In addition, there also exist in the Czech Republic other deposits having verified reserves of uranium ores, which could be mined under certain conditions. In connection with the continuation of mining and the future exploration of the Rožná deposit, it is appropriate to consider the possibilities for exploiting the uranium deposits of Brzkov and Věžnice, which are parts of the Moravian ore district and show a similar geological structure and ore mineralization as the Rožná deposit. According to the reserve estimation carried out after the completion of geological exploration by mining exploration on the 3^{rd} and 5^{th} level in 1992, the overall estimate of explored reserves, prospected reserves and inferred resources in the deposits of Brzkov and Horní Věžnice is 4825 t of uranium. The volume of extractable reserves thus determined is 2 070 000 t of ore, which represents about 3100 t of uranium.

It can be expected that the next intensive geological exploration of already mined uranium deposits will expose reserves that were either unknown in the course of previous mining operations, or were not mined for various reasons. However, the volume of newly localized reserves would probably not be significant, and the mining of them in deposits under the conditions of mines already closed is unrealistic.

A quite different situation is in the area of North Bohemian Cretaceous Formation, where the deposits of Hamr (underground mining) and Stráž pod Ralskem (in situ leaching) were intensively mined before the mid-nineties. These days, the underground mine is completely decommissioned and in the area of chemical mining, an expensive remediation of the rock environment is taking place. But it is necessary to emphasise that the known geological reserves in this area amount still to about 110 000 t of uranium, being registered now as out-of-balance (sub-economic). With regard to the complicated hydrogeological conditions of the area, only about a half of them may be classified as extractable, which nevertheless represents a potential source of raw material that is highly significant to the Czech nuclear power industry. At present, the revival of uranium mining in North Bohemia is not possible for many reasons and would not be acceptable to the public. Nevertheless, nothing prevents professionals from conducting discussions leading to the search for a suitable method of exploitation, treatment technologies and solutions to relate ecological problems so that they might be prepared should a situation develop requiring mining operations even in this area.

UTILIZATION OF MINE WATERS AS SECONDARY SOURCE OF URANIUM

It is the research task covered by the grant project GAČR No. 105/06/0127, “Non-traditional utilization of uranium deposits after finishing underground mining”, that deals with possibilities of using non-traditional methods for obtaining uranium. The project concerns the utilization of mine waters of flooded uranium mines as a source of uranium with the accompanying effect of shortening the time period necessary for the purification of mine waters discharged into surface watercourses. This is because the mine waters of flooded former uranium mines represent, in view of their considerable volumes and high concentrations of dissolved uranium, a significant secondary source of this raw material. The idea for utilizing mine waters of flooded uranium mines as a secondary uranium source is based on the natural process of dissolving uranium materials in mine waters after their previous oxidation in the stage of deposit exploitation. To a certain extent, this is analogous to the mining method “in situ leaching”, but where the process of uranium transfer to the solution is intensified by adding acids into the rock environment, natural processes are utilised instead. If the present intention is confirmed by theoretical calculations, mathematical modelling and a pilot trial, this will make it possible, in the course of any plan being subsequently implemented, to acquire a non-negligible amount of uranium (for example, in the waters of the flooded uranium deposit at Příbram, the upper estimate is of hundreds of tonnes of uranium). The subsequent effect of shortening the time necessary for mine water purification, which is financed in the Czech Republic from the national budget, would likewise be significant.

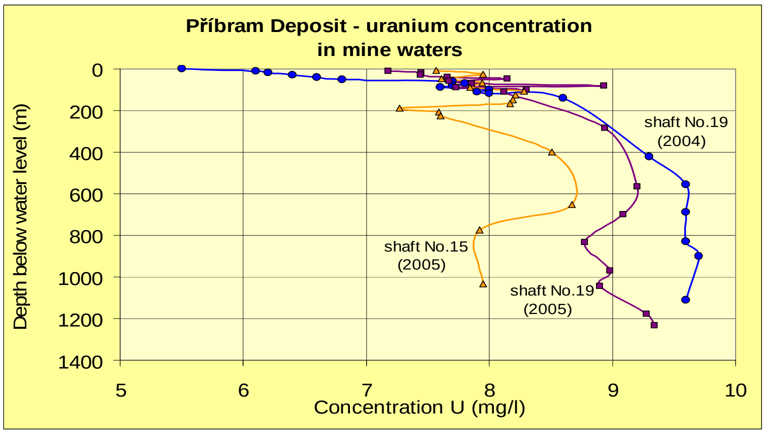

FIG.7. Uranium concentration in mine waters of the flooded deposit of Příbram depending upon depth.

The problems being solved are associated with the geochemical regime of mine waters after the flooding of the mine. After the decommissioning of the mine, the concentration of uranium (but not only of uranium) in waters markedly grows together with the process of flooding. Then a significant vertical stratification of mine waters develops in the course of time. This is conditioned especially by the minimization of mine water flow after the disappearance of the hydraulic gradient earlier induced by the active drainage of the mine. These rules are recognized as common to almost all underground ore and coal mines. It follows from this that in deeper horizons of the former mine, uranium concentrations in waters are higher than in near-surface parts of the mine (Figure 7).

Partial results of the aforementioned research task, obtained at the flooded Olší–Drahonín deposit, have established that there indeed exist accumulated mine waters with a relative high content of uranium in the deeper part of the flooded uranium mine, which might be used as a secondary source of uranium. From the point of view of the easy purification of drained waters, an unambiguous requirement exists for the drainage of near-surface waters, i.e. waters with the minimum contents of dissolved substances; on the other hand, from the point of view of maximization of the yield of uranium from mine waters, it would be desirable to drain waters with high uranium concentrations, i.e. from deeper parts of the mine.

CONCLUSION

From 1945 to the mid 1990s, the uranium mining industry was an important industry in the Czech Republic and in the production of uranium concentrate, the Czech Republic occupied a prominent position in the world. The exploitation of uranium deposits was conducted very intensively, primarily by using the underground method of mining. Since the end of the 1980s, the production of uranium ore has however decreased owing to the exhaustion of some deposits and above all owing to a marked drop in sales as a result of political-economic changes. At present, mining operations are only performed in one underground mine in the deposit of Rožná for the needs of Czech power industry. Nevertheless, the uranium mining industry still represents a significant domestic source of raw material for the Czech power industry. With regard to present developments in the consumption of raw energy materials in the world, the increasing dependence of many countries including the Czech Republic on imports of raw energy materials, often from politically unstable regions, it is undoubtedly strategically desirable to keep the production of uranium in the Czech Republic for the needs of the domestic power industry. The preconditions afforded by the raw material basis and the conditions for the mining of uranium in the territory of the Czech Republic still exist.

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REMEDIATION OF THE SILLAMÄE RADIOACTIVE TAILINGS POND, ESTONIA*

U. Barnekow[1], *R. Jaaksoo*[2], *T. Kaasik*[2]
[1] Wismut GmbH, Chemnitz, Germany
[2] Ökosil Ltd., Tallinn, Estonia

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Abstract

The paper presents experiences gained and progress achieved during the ongoing Sillamäe Radioactive Tailings Pond Remediation Project. The Sillamäe tailings pond covering ca. 50 ha is located next to the shoreline of the Baltic Sea near Sillamäe town in Estonia. Tailings disposal included mill tailings from uranium ore processing (1953–1977), enriched uranium refining (1977–1990), from rare earth elements processing (since 1970; tailings disposal ended 2003), black shale processing (1948–1953) and liquid oil-shale ashes from the local power plant. Initial environmental and geotechnical investigations identified insufficient safety of the tailings pond for radiological, environmental and geotechnical reasons. Contaminated seepage was entering the Baltic Sea. The 25 m high northern tailings dam was affected by marine erosion and the stability of the dam was found to be insufficient. Therefore the multi-national Sillamäe Radioactive Tailings Pond Remediation Programme was launched in 1998 jointly financed by North European Countries (NEFCO), EU and Estonia. The remediation project included the following crucial remediation steps: Drillings and samplings including geotechnical, (hydro-)geological and environmental investigations (2000–2001); relocation of mine wastes and contaminated soils from the surrounding area onto the tailings pond for interim covering (2000–2003); initial stabilization measures (2001–2003) including a 1080 m long shore protection embankment along the shoreline of the Baltic Sea, a 720 m long pile grillage for stabilizing the northern dam including two rows of 15 m or 18 m deep continuous flight auger piles, a 580 m long and 12-18 m deep cut-off wall, a deep gravel-filled drainage ditch (520 m, up to 12 m deep) and a deep drainage trench. Reshaping of the dams with respect to long term dam stability and contouring of the pond area with respect to long term settlement portions lasted from 2003 till 2004 building up a ridge-type surface contour. Final covering started in 2005 and shall be completed in 2009. The multi-layer type final cover consists of a sealing layer (min. 30 cm), a drainage layer (min. 30 cm), a suffusion prevention layer (min. 20 cm), a storage layer (min. 100 cm) and a vegetated 30 cm thick recultivation layer on top. The paper finally presents an outlook for the long term monitoring after closure.

INTRODUCTION

The Sillamäe Tailings Pond is located next to the shoreline of the Baltic Sea near Sillamäe town (17 000 inhabitants) in Eastern Estonia. The tailings pond covers an area of 50 ha and includes a volume of 8 million m^3 of tailings. Tailings from uranium ore processing, from rare earth elements, in particular Niobium and Tantalum processing and liquid oil-shale ashes from the local power plant have been discharged into the tailings pond.

Initial evaluations carried out after Estonia´s independence in the 1990´s identified insufficient safety of the Tailings Pond for radiological, environmental and geotechnical reasons. Contaminated seepage was entering the Baltic Sea. At about 25 m high, the northern tailings dam was affected by marine erosion, and dam safety was found to be insufficient.

Therefore the multi-national Sillamäe Radioactive Tailings Pond Remediation Project was launched in 1998 jointly financed by Norway, Sweden, Finland and Denmark, Nordic Environmental Finance Corporation (NEFCO), European Union and Estonia.

ÖKOSIL Ltd. (Tallinn, Estonia) became responsible for project steering as well as for implementing the newly developed radiation protection program and is the employer for all decommissioning works. Since 1997 Wismut GmbH (Chemnitz, Germany) has continuously been involved in the project. Wismut GmbH was responsible for the design and planning work for the stabilization, the recontouring and the surface cover construction. Currently Wismut GmbH is reponsible for monitoring of the ongoing construction works. For daily on-site-monitoring of the construction works Wismut GmbH has contracted the Estonian company IPT Projektijuhtimine, Tallinn.

The paper presents the design of stabilization measures and of the remediation of the Sillamäe Tailings Pond. Furthermore it presents progress achieved still to date and experiences gained during ongoing remedial works. The remediation of the tailings pond shall be completed by 2009 followed by a period of long term monitoring after closure.

HISTORICAL BACKGROUND

The uranium processing plant (SILMET) located at Sillamäe, Eastern Estonia, was launched in 1948 to process Uranium ores mined from the local Dictyonema alum shale resources (U up to 300ppm). Later on, uranium ores from other countries, notably from Czechoslovakia, Hungary and to a lesser amount from Eastern Germany, were milled and processed by acid leaching (U in ore up to 1%). Black shale processing lasted from 1948 till 1953. Uranium ore processing started in 1953 and went on till 1977. Enriched Uranium refining lasted from 1977 till 1990. In addition since 1970, loparite has been processed by SILMET to gain Niobium, Tantalum and further rare earth elements.

Tailings disposal started in 1948 discharging tailings directly onshore next to the shoreline of the Gulf of Finland (Baltic Sea). Beginning in 1959, several individual impoundments were built up forming the lower layer of the Sillamäe Tailings Pond. Dam crest levels of starter dams and of internal compartment dams were raised step-wise according to the needs of the ongoing tailings disposal. The Sillamäe Tailings Pond was subject to various modifications until it reached its current size during the 1970s. During the disposal period, tailings overtopped the dam crest of the Tailings Pond several times.

In 1993 the Sillamäe Tailings Pond contained about a total of 12 Mt (about 8 Mill. m^3) enclosing 6.3 Mt uranium mill tailings and 6.1 Mt of oil shale retorting wastes (ash tailings) from the local power plant. In addition there are several 100 000t of loparite processing wastes and further production residues. Continuous disposal of oil shale retorting wastes ended in 1990. The discharge of tailings from processing of rare earth elements ended during ongoing remediation in 2003.

After Estonia’s independence initial geotechnical investigations and risk analyses were carried out in 1993/94. At that time the dam toe of the north-western tailings dam was affected by wave erosion at the shoreline of the Baltic Sea. In addition preliminary dam stability calculations resulted in insufficient safety of certain cross sections of the seaside tailings dam. Therefore geodetic survey points were installed on the tailings dams in order to measure time dependent deformations of the Tailings Pond. Secondly, prior to remediation, the radioactive impact via direct irradiation exposure was way above the generally accepted levels for the general public, even for professional operators under special surveillance. Radon levels in the nearby town of Sillamäe were above intervention levels applicable in similar situations in the EU. Dust containing radioactive particles was easily blown away from the Tailings Pond surface, in particular from the subaerial tailings beaches.

First defense measures against the above mentioned acute risks were taken already in 1996 by building up a local shore protection embankment in front of the north-western part of the seaside tailings dam. Reprocessing of radioactively contaminated tailings had to be excluded as a suitable remediation option in 1998 [1]. In 1998 the multi-national Sillamäe Radioactive Tailings Pond Remediation Programme was launched jointly financed by North European Countries (NEFCO), EU and Estonia. Figure 1 shows the Sillamäe Tailings Pond before the start of the construction works in 1999. Figure 2 presents the situation during ongoing interim covering and re-contouring works in 2002. Figures 3 and 3a show the status during ongoing final covering achieved by August 2007.

FIG.1. Sillamäe Tailings Pond in 1999 (view westward).

FIG.2. Sillamäe Tailings Pond in 2002 (view eastward).

FIG. 3. Sillamäe Tailings Pond in August 2007 (view westward),
FIG. 3a (inset): Sillamäe Tailings Pond in August 2007 (view southward) ongoing final covering in the foreground along the Eastern pond and Eastern dam slope area.

SITE CHARACTERIZATION

In 1999 Wismut GmbH reviewed all historical, geotechnical and environmental data available and assessed preliminarily the relevant acute dangers and environmental and geotechnical risks. Based on this preliminary assessment the Sillamäe Radioactive Tailings Pond Remediation Project launched previously, was structured in detail. During the following years extended geological, geotechnical and hydrogeological investigations were carried out on the site to gain a sufficient database for decision making and for detailed design planning of the remedial measures needed.

The Sillamäe Tailings Pond was established on a highly permeable quaternary layer of marine sand and gravel, underlain by very low permeable Cambrian clay. The Cambrian clay is over-consolidated. The uppermost few meters consist of weathered Cambrian clay of semi-solid consistency. The degree of weathering decreases with depth. Underneath the weathered Cambrian clay, a fissured Cambrian clay layer follows underlain by the unaltered Cambrian clay. The origin of the fissures within the clay can be explained by internal shearing of the clay layer caused by moving glaciers during glacial periods. The existing Cambrian clay surface developed as an ancient erosional surface dipping at 2–3° towards the sea. Onshore the Cambrian clay is covered by glacial sediments such as silty moraines and sands with a thickness of several meters. On top of the sequence a marine sandy gravel layer (thickness several meters) is covering either the glacial sediments and/or the Cambrian clay. To the hinterland and along the landside dam of the Tailings Pond the Cambrian clay is covered by weathered Cambrian/Ordovician sandstone (thickness up to about 20 m) which incorporates some local shale layers. Along the landside dam of the Tailings Pond the upper surface of the sandstone has been identified to be an ancient cliff consisting of several terraces. In this sandstone cliff area the terrace surfaces are covered by quaternary silty moraines and sandy layers. More to the hinterland the Ordovician sandstone layer is overlain by a 1–1.5 m thick Ordovician oil shale layer which itself is covered by an up to 16 m thick Ordovician limestone. The Ordovician Dictyonema (alum) shale has partly been mined by underground mining during the late 1940´s. Figure 4 shows the internal structure of the tailings pond and the geological layers underneath.

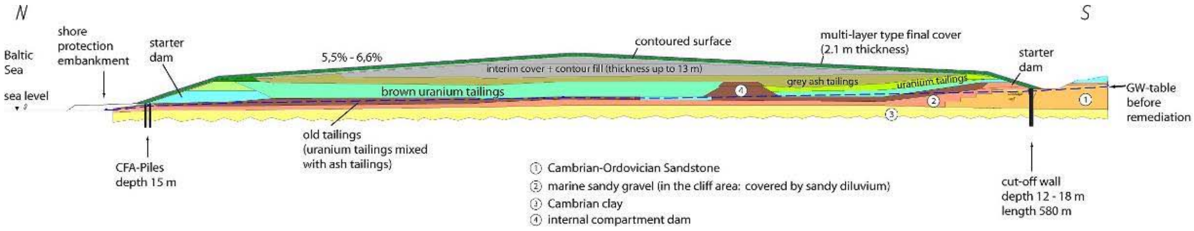

FIG.4. Cross section of the Sillamäe Tailings Pond (N-S) including the underground layers.

The Cambrian clay is an about 70m thick regional aquiclude separating the near surface aquifer from a deeper second aquifer. The deeper aquifer is not affected by the Sillamäe Tailings Pond. The near surface aquifer consists of the Ordovician limestone and the underlying Cambrian to Ordovician sandstone. The 1.0–1.5 m thick oil shale layer in between both layers does not act as an impervious layer because it was partly mined in the relevant recharge area. Therefore groundwater flow is also controlled by drainage tunnels installed due to former underground mining. Groundwater flow is directed from the recharge area in the hinterland via the Ordovician limestone layer northward to the underground mining area. In the mining area groundwater is partly drained to the surface by drainage tunnels, but seeps partly into the underlying Cambrian-Ordovician sandstone aquifer layer being diverted to the ancient cliff area at the landside dam of the Sillamäe Tailings Pond. Before remediation started groundwater entered sewers the Sillamäe Tailings Pond at the landside dam and was drained by the marine gravel layer to the Baltic Sea. Figure 4 shows the groundwater table measured in 2001 falling in direction to the shoreline. At that time tailings layers were in contact with groundwater. In addition process waters and infiltrating surface waters were seeping through the tailings into the underlying marine gravel layer. Contaminant seepage into the Baltic Sea contained a huge amount of nitrogen components and further more soluted metals from ore processing, thus violating the Helsinki convention.

SILLAMÄE RADIOACTIVE TAILINGS POND REMEDIATION PROJECT

Preparatory Phase

Preliminary environmental assessments in 1998 led to the conclusion that there is an urgent need to reduce contaminant seepage into the Baltic Sea. Evaluation of geotechnical data resulted in insufficient geotechnical stability, in particular of seaside tailings dam. Radiological assessment of the air pathway identified an urgent need to reduce the radioactive impact caused by dusting and radon exhalation.

The Sillamäe Radioactive Tailings Pond Remediation Project, jointly financed by the European Union, North European Countries (Nordic Environmental Finance Corporation NEFCO) and Estonia was launched in 1998 covering a project volume of 20 mllion euro. The general objective of the project is to assist the Government of Estonia in the remediation of the Sillamäe Radioactive Tailings Pond, in order to reduce the emissions to water and air and to attain compliance with the EU directives on nuclear safety and radiation protection, on waste water and with the Council Decisions regarding the Protection of the Marine Environment of the Baltic Sea (Helsinki Convention, 94/157/EC).

For preparing a detailed conceptual design of the environmental liabilities caused by the Sillamäe Tailings Pond a pilot project was launched by the European Commission within the frame of the PHARE Multi-Country Environmental Programme. During this conceptual design phase the Sillamäe Radioactive Tailings Pond Remediation Project was structured into three basic decommissioning steps, which are dam stabilization and protection of the dam toe against marine erosion, interim covering and recontouring of the entire tailings pond and at last placement of a final cover. ÖKOSIL Ltd. (Tallinn, Estonia) was established for project steering, as the Employer of the decommissioning works and for implementing a radiation protection program newly developed.

Conceptual Design Phase (1998 – 2000)

Wismut GmbH (Chemnitz, Germany) and C&E Consulting and Engineering GmbH (Chemnitz, Germany) jointly prepared a Detailed Conceptual Design for Decommissioning of the Sillamäe Radioactive Tailings Pond. Based on the review and evaluation of all historical, geotechnical and environmental data available a decision was made to plan for dry decommissioning in situ as the best suitable option. In addition detailed environmental and geotechnical investigation programs were planned as a basis for the final design phase.

The Detailed Conceptual Design included the following remediation works:

- Dam stabilization of the seaside tailings dam with respect to short term stability by a double row of 15 m or 18 m deep continuous flight auger piles along the seaside dam toe where needed with regard to given insufficient geotechnical safety.
- Construction of a shore protection embankment along the shoreline.
- Construction of a water diverting system consisting of a cut-off wall and a deep drainage trench to divert the groundwater recharge from the hinterland. With respect to contaminant seepage into the Baltic Sea annual groundwater seepage rate entering sewers the Sillamäe Tailings Pond from the hinterland had to be reduced to below 30 000 m^3/year. In addition the groundwater table should be kept underneath the tailings layers.
- Construction of a multi-layer type final cover to reduce the annual infiltration rate from precipitation to below 20 000 m^3/year.

Design and construction of initial stabilization measures (2000–2003)

Based on the conceptual design prepared as part of the pilot project the first stage of interim covering of the tailings beaches and contouring of the landside part of the Sillamäe Tailings Pond lasted from 2000 to 2002. Figure 1 shows an air photo of the tailings pond before start of the construction works in 1999. Figure 2 shows the situation of summer 2002 during ongoing interim covering and re-contouring on the tailings pond. The active ash pond for disposal of oil shale retorting wastes located in the foreground of Figure 2 will be closed in 2009. Figure 3 and Figure 3a show the situation during ongoing final covering in August 2007. At that time the final cover placement proceeded on the Eastern area of the tailings pond.

The final design of initial stabilization measures was prepared under a FIDIC contract. WISMUT was contracted by ÖKOSIL as Consultant for Technical Assistance to review and supervise the detailed planning and the construction works on the site. The realization of all initial stabilization measures design phase started in 2001. The construction phase ended in 2003. A geotechnical field and lab investigation program was carried out in 2001/02 in order to gain data needed for final design of the entire remediation. The final design of the initial dam stabilization included a total of 455 continuous flight auger piles (concrete piles, diameter 550 mm) installed in a double row along the seaside dam toe and reinforced by HEA 140 steel beams. 130m along the northwestern dam toe and 560m along the north-eastern dam toe were stabilized by piles of 15 m or 18 m depth. A 1080 m long shore protection embankment was constructed in 2001–2002. The position of all initial stabilization measures is presented in Figure 5.

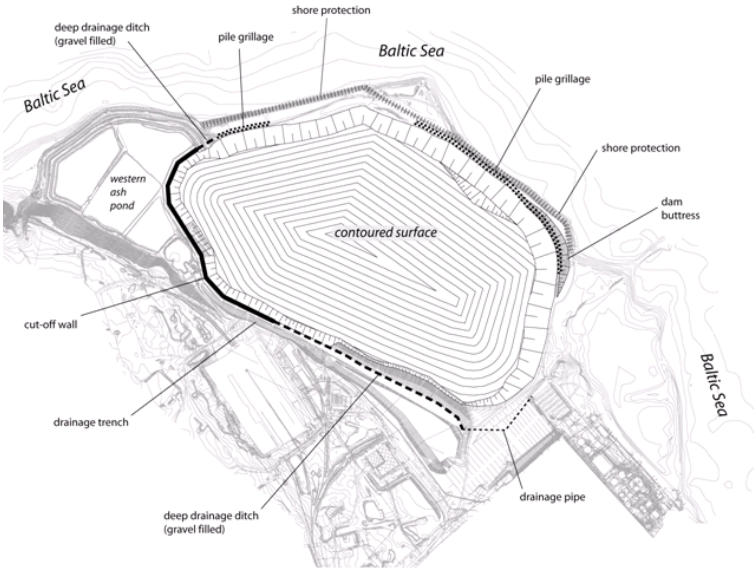

FIG.5. Schematic site map: Sillamäe Tailings Pond (status after stabilization and re-contouring).

A water diverting system was designed to guarantee the required maximum annual inflow rate of 30 000 m^3/a in a wet year (after surface covering of the tailings pond). The water diverting system consists of a 580m long and 12–18 m deep cut-off wall along the south-western part of the tailings pond and a large drainage trench in the south-eastern area of the tailings pond. Installed within this drainage trench is a gravel filled drainage trench with a capacity of up to 12 m in depth, starting from the cut-off wall. The gravel-filled drainage trench drains the surface and groundwaters eastward to the Baltic Sea. The cut-off wall consists of a bentonite-cement mixture and was installed continuously in one phase as a fluid slurry pulp. It reaches down to at least 1 m below the surface of the Cambrian Clay.

Final design and construction of re-contouring of the tailings pond 2002–2005

In 2002 Wismut GmbH prepared the detailed design and construction planning for dam reshaping, remaining interim covering and recontouring of the Sillamäe Tailings Pond. Dam reshaping was designed with respect to the long-term dam stability. Under the site conditions the residual shear strength of the Cambrian clay, in particular the uppermost weathered Cambrian clay layer, is of critical importance. Dam stability was calculated for 15 dam sections using PLAXIS finite element code. Resulting from the dam stability calculations the dam reshaping was designed individually for each cross-section. In most cross-sections the tailings dam was reshaped from the dam toe inside the pond area to a slope fall ratio of v:h = 1:3. Locally the dam was reshaped v:h = 1:4…1:5 in particular the eastern corner area of the seaside tailings dam was to be reshaped by dam buttressing and reshaping of the upper slope inside the pond. The surface contour of the recontoured pond area was designed with respect to guarantee the functionality of the future final cover over the long term. For this a minimum slope fall of 5% of the final cover shall be granted to the long term. WISMUT designed the pond area as a ridge-type surface contour, containing a total volume of about 2.2 Mill. m^3 of fill. The maximum total settlement underneath the ridge was calculated to be 2.4 m. This led to individual slope inclinations on the pond area varying from 5.5 to 6.6%. Re-contouring works lasted from 2003 until 2005. Mine wastes and radioactively contaminated soils and debris from the surrounding industrial site were relocated into the placed fill layer as well.

Final Design and Construction of the Final Cover 2004 – 2009

The final cover was designed in 2004/05. The final cover is currently being placed on the recontoured surface of the tailings pond. Final covering started in 2005. By the end of 2007 the final cover had been placed on ca. 38 ha of a total pond area of ca. 50 ha. Final cover construction shall be completed by autumn 2009 at the latest. All construction works are supervised by Wismut GmbH and monitored on the site on a daily basis by our local representative IPT Projektijuhtimine, Tallinn.

According to the requirements presented above, the final cover shall reduce the annual infiltration rate to below 20 000 m^3/a and has to reduce the radon exhalation rate to reasonable values. It must be stable against surface erosion, hydraulic failure, differential settlements, disturbance of the sealing layer by air-drying or by frost over the long term. Detailed dimensioning of the final cover system was prepared based on a water balance model of the final cover using the HELP code. To meet the required maximum infiltration rate a multi-layer type final cover was designed. From bottom to the top the multi-layer type final cover consists of a sealing layer of a compacted clay ($k_f \leq 1*10^{-9}$ m/s, min. 0.30 m), a drainage layer (min. 0.30 m) made of crushed limestone gravel, a suffosion prevention layer (min. 0.20 m) made of crushed limestone fines, a storage layer (min. 1.00 m) made of sandy loam and a recultivation layer (min. 0.30 m). Finally grass is to be seeded on the final cover surface.

Monitoring after Closure

With respect to the end of the decommissioning phase and the following after-care phase a monitoring system is built up under the Sillamäe Radioactive Tailings Pond Remediation Project in order to prove the following items: functionality of the final cover as built; functionality of the water diverting system as built; control of contaminant seepage, dam stability and radiation protection.

Lysimeters are implemented in the final cover to measure the percolation rate through the final cover. In total 21 groundwater wells have been be installed to monitor groundwater flow entering the Tailings Pond and flowing into the Baltic Sea. Contaminant seepage will be monitored by groundwater sampling and chemical analyses. Vertical inclinometers and pore pressure gauges installed in the Cambrian clay layer are used to measure, if there is any, movement of the seaside dam. Groundwater monitoring wells in the dam area measure the seepage line in the dam. Geodetic measurement points are installed on the pond area in a grid of 50 m by 50 m and on the dam shoulder lines to measure spatially the time-dependent deformation of the final cover surface.

In addition a separate radiation protection program including regular monitoring was implemented in the past to control all relevant exposure pathways from the tailings pond to the surrounding environment and to human beings during the remediation phase. The monitoring program needed with respect to the long term is currently being prepared.

ACKNOWLEDGEMENTS

We would like to thank Mr Talviste and Mrs Sedman, IPT Projektijuhtimine (Tallinn, Estonia) for their excellent support regarding the on-site monitoring of the construction works.

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THE URANIUM MINING LEGACY OF EASTERN GERMANY: FROM REMEDIATION TO REGIONAL DEVELOPMENT©

M. Hagen, A. T. Jakubick
Wismut GmbH, Chemnitz, Germany

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Abstract

The prime justification for remediation of the legacy of the former SDAG Wismut is derived from the German Mining Law, which already several hundred years ago stipulated the orderly closure of mines and mitigation of damages caused by mining. The more recent legislation served to protect the water supplies and cover the specific of uranium mining issues, such as radiation protection. The extent of remedial measures was derived by investigation of the remediation feasibility and environmental impact for each case of the Wismut legacy individually. Unlike for common civil engineering projects, the remediation workflow turned out to be an iterative process with feedback loops. Conceptual Site Models (CSM) proved to be an efficient guide for optimization of remedial designs and focusing data acquisition at complex sites. The monitoring activities comprised the monitoring of the remedial works and monitoring of the impact on the environmental baseline. The collected data are analysed, evaluated and employed to provide decision-making support. In the present, advanced stage of the Wismut remediation project the utilization of the reclaimed areas and remediated mining waste piles s in the focus of attention. There are no restrictions regarding use for areas, which received a complete clean-up. Utilization of areas, waste rock piles and tailings ponds reclaimed for restricted use is restricted to forestation or settlement of industry and trades. Exemptions are possible if the responsibility for long term stewardship is satisfactorily resolved. Successful integration of remediation with communal/regional developmental plans resulted in re-establishment of a health spa in the town of Schlema and revitalization of the mining towns of Gera and Ronneburg hosting the biannual Federal Horticultural and Landscape Exhibition in 2007 (BUGA 2007), which was partly located on the remediated Wismut legacy site.

DECREASE OF URANIUM DEMAND, CLOSURE OF MINING AND THE LEGACY OF SDAG WISMUT

During the cold war era, the Soviet-German joint stock company SDAG Wismut produced more than 216 000 t of U_{met}. The uranium mining and processing was spread over an extensive area of Eastern Germany, particularly in the present states of Saxony and Thuringia (Figure 1).

The sole customer of the production was the Soviet Union government. Because the uranium ore grade at most of the mining sites was low, the extensive production generated perhaps the largest uranium mining legacy in the world. The first signs of decreasing demand of the Soviet government for uranium started in the late 1980s. After the German reunification (1998) the mining was stopped for economic reasons in December 1990. The inventory of the uranium production legacy at this time was as follows:

- operational areas (37 km^2);
- five large underground mines;
- an open pit mine (84 Mm^3);

- waste rock dumps (311 Mm^3); and
- mill tailings (160 Mm^3).

The specific activity of the waste rock was 0.5 to 1 Bq/g and of the tailings up to 10 Bq/g.

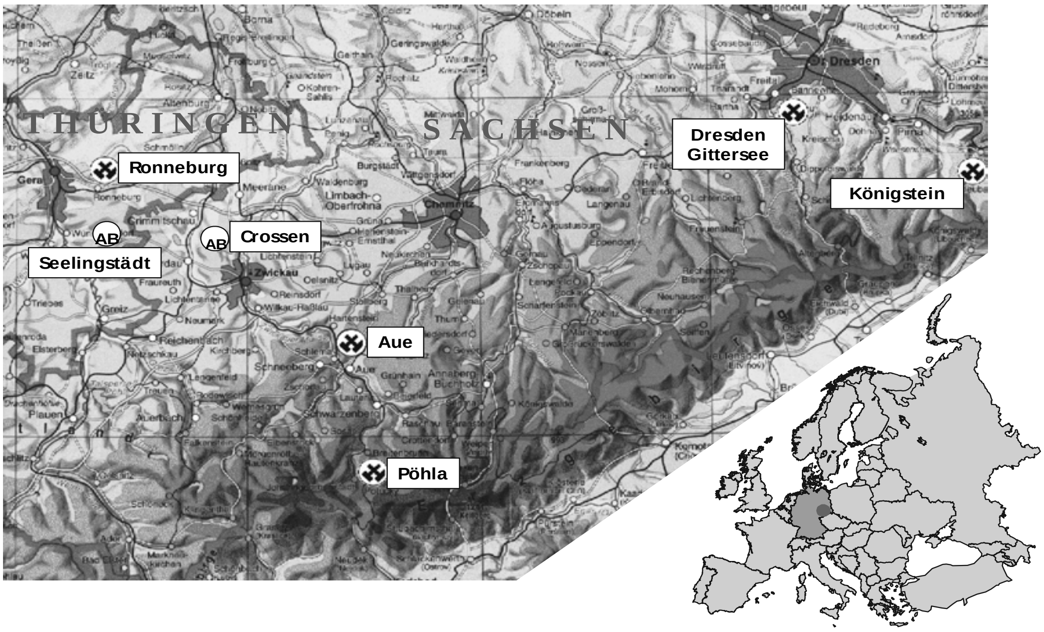

FIG. 1. Mining and milling sites of Wismut.

SIMULTANEOUS PREPARATION AND IMPLEMENTATION OF THE MOST URGENT REMEDIAL MEASURES

With passing of the “Wismut Act” in the Federal Parliament in December 1991 the road to remediation of the SDAG Wismut liabilities became open. Based on the act the Federal Government committed €6.6 billion (later revised to €6.2 billion) to the environmental remediation and social mitigation of the liabilities of SDAG Wismut. For the implementation of the task the national corporation Wismut GmbH was founded.

The legislative framework was provided by the (1) “Federal Mining Law” (*B BergG*) stipulating the owner’s obligation to abate public hazards and mitigate damages caused by mining as well as prevent hazards after mine closure; (2) “Ordinance for provision of radiation protection for waste rock dumps and industrial settlement ponds and for use of materials deposited therein” (*HaldAO*) regulating the radioactive aspects of remediation and (3) “Water Resources Management Act” protecting surface and ground water resources.

At the beginning of the remediation program there was no uranium mine closure experience available in Germany and in order to simultaneously commence both engineering and remedial works without delay, extensive use had been made of the experience available internationally. Cooperation was sought with the US Department of Energy’s UMTRA Project and the relevant institutions and companies in Canada[1]. Yearly international topical

[1] A Memorandum of Understanding was signed with the Canadian Ministry of Mines and Natural Resources, MNMR and with Atomic Energy Control Board, AECB (the predecessor of the present Canadian Nuclear Safety Commission, CNSC), May 1991.

workshops were organized at Wismut to foster know-how acquisition and to identify suitable technologies for the remediation. The introduction of regular meetings of the Uranium Mine Remediation and Exchange Group (UMREG) served as a platform for international peer review of the envisaged concepts, methodologies and regulatory approaches.

Prior to commencement of the remediation, an area of approximately 100 km^2 was investigated in a large scale gamma radiation survey in 1990. The purpose of the survey was to appraise the extent of contamination in the areas affected by the activities of the former SDAG Wismut. The initial characterization survey narrowed down the extent of the radioactively contaminated land (i.e. contaminated beyond background level) to approximately 15%, thus releasing a substantial area for unrestricted use. After the initial survey, the remedial investigations and works focused on five mining sites (Ronneburg, Aue/Schlema, Pöhla, Königstein, Gittersee) and two mill sites (Seelingstädt and Crossen).

Conceptual remedial designs and closure plans were developed for each site, often concurrently with the preparation of detailed designs and remedial work plans. Only at a later stage of the program became possible to standardize procedures and establish a work routine. The remedial works were then reorganized into 14 projects coordinated from 3 Site Management Units (Ronneburg, Aue and Königstein). Strategic direction, feedback, optimization and specialists support continued being provided from the Head Office in Chemnitz.

Decision making tools

Besides preparation of the remedial concepts, the engineering work focused on the investigation and specification of the type and extent of the remedial measures and on the study of their feasibility (RI/FS). Along with the RI/FS the environmental impact (EIA) of the remedial measures was assessed. By using this approach the decision making process could be kept transparent and traceable and the extent of the remedial measures justifiable. The specific feature of this approach is that the extent of remediation is related to the level of risk of each contaminated site, waste rock pile or tailings pond. Beyond being more realistic, the risk based approach provided for a better economics than the application of prescriptive environmental limits.

The radiological impact was assessed based on calculation of the effective individual dose for realistic release and uptake scenarios. If the calculated dose was in excess of the background level and exceeded the 1 mSv per year level – a limit recommended by the International Commission for Radiation Protection (ICRP) – the remedial measure was adjusted such (e.g. the cover thickness increased etc.) to decrease the effective individual dose below the 1 mSv per year. Along with the radiological impact assessment, the regulated limits for conventional contamination were observed as well. For instance, arsenic, a commonly occurring contaminant at the sites in the Ore Mountains (Erzgebirge), placed sometimes stricter limits on the remedial measures that the calculated effective individual dose. In such cases the remedial design followed the most stringent among the applicable limits. The optimization of the remedial measures was based on cost/benefit analyses and comparison of the options. In cases where socio-economic factors entered the decision making, a multi attribute analysis was employed.

Decisions involving large remedial investments, such as the decision whether to remediate the Helmsdorf tailings pond as a dry landform (a “dry” remediation) or remediate by maintaining a stable water cover over the tailings (“wet” remediation) was supported by a probabilistic risk assessment. For both options the cumulative probability of various tailings pond/dam failure scenarios was related to the equivalent costs (sum of costs for remediation, water treatment, maintenance, failures (including resulting clean-up costs) and repairs minus the health and environmental benefits [1]. The possibility of relocation of the tailings was excluded because of the high costs and the lack of a suitable disposal site.

The results of the risk analysis are presented in Figure 2 in terms of cumulative probability of equivalent costs over the lifetime of the remediated tailings pond. Figure 2 shows that if only 50% of the realistically possible failures over the life time of the tailings pond/deposit are considered, the costs of a wet remediation (similar to the solution implemented at Elliot Lake, Ontario) would be approximately 150 million € less than for a dry remediation. However, if more than 65% of the locally possible failures are considered, the dry remediation becomes clearly more cost efficient than the wet remediation. Considering that the main dam of the Helmsdorf tailings pond was approximately 78 m high and located only 150 m upstream of the community of Oberrothenbach, a 95% level of safety over the life time of the tailings deposit was demanded by the local community. Because the possibility of a seismic even at the site could not be eliminated over the life time of the tailings pond, the required level of safety could only be attained by turning the tailings pond into a dry landform, thus preempting the possibility of liquefaction of the tailings.

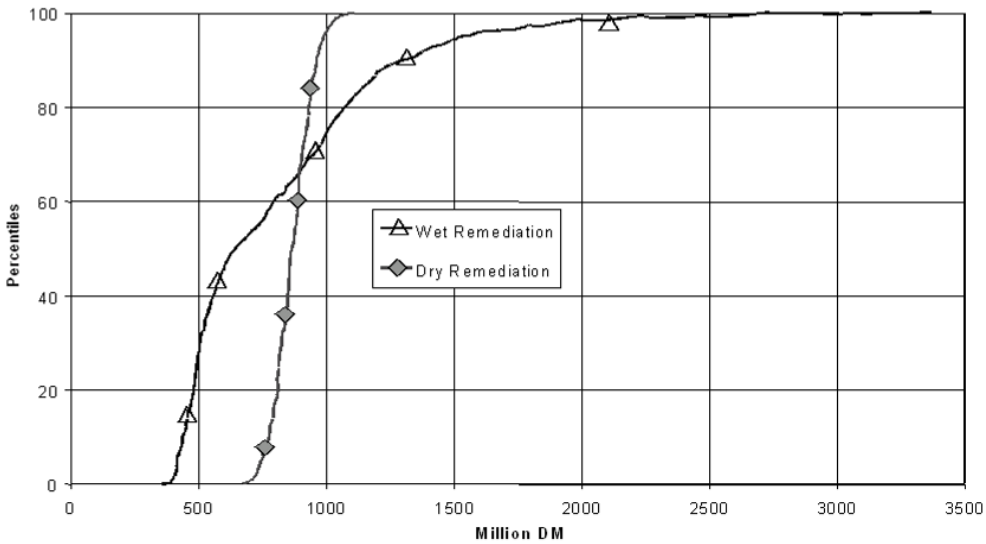

FIG. 2. Cumulative Probability of the Equivalent Costs for the Wet and Dry Tailings Remediation Options at the Helmsdorf site.

On a more general level, the case of Helmsdorf illustrates that formal approaches in remediation (cost/benefit, multi-attribute analysis and probabilistic risk assessments) are useful for comparison of remediation options but the decision-making ultimately depends on the parameters defined jointly with the stakeholders.

Conceptual Site Models (CSM) proved to be an effective tool for both technical planning and regulatory negotiations in case of complex sites with collocated contaminant sources that interact [2].

Cover designs

All remediated (dry) tailings deposits or waste rock piles (whether remediated *in situ* or relocated into the open pit) receive at the end a final soil cover designed to reduce radiation, radon exhalation, and limit infiltration and support vegetation on the surface. A large number of cover types were used in international projects, a comparison of which was presented at UMREG 2002 [3]. At Wismut, several types of cover systems have been implemented, pending on the specific remediation goal for a particular pile or site.

For the partially acid generating waste rocks in Ronneburg, basically two different cover system have been used, one for covering the backfilled open pit mine and an other for covering of the central Beerwalde waste rock pile [4].

For the waste rock piles at the Schlema mine site, which are not acid generating, a two-layer cover system has been developed. The specific problems at the site were to find feasible cover construction technologies for steep slopes (1:2 to 1:2.5) and reduce effectively the high radon emanations from the piles in critical vicinity to residential areas. A cover design resembling the indigenous soil profiles proved to be a suitable solution. The covers design implemented avoids any smooth layering, thus preventing the creation of potential sliding planes. The relatively simple, 1 m thick, two-layer cover system (Figure 3) showed an excellent performance during the extreme rainstorms and river floods in 12 to 13 August 2002. During the two days, the rainfall exceeded the hundred year projected limits by several times and was rated as the highest rainfall expected in thousand years. Wherever the cover has been completed and the vegetation established, no damages to the cover occurred. Based on this unexpected natural test it was concluded that the implemented cover is resilient against erosion by rainfall.

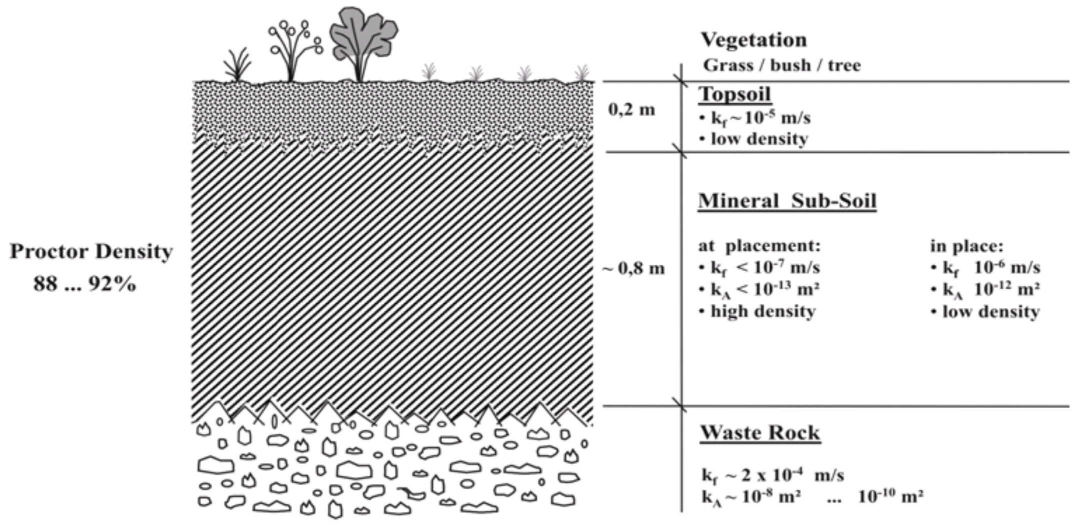

FIG. 3. The two-layer cover system emulating natural soils used on steep pile slopes in the Ore Mountains (Erzgebirge).

A key parameter of performance for a cover placed on uranium mining waste is the radon attenuation. A novel type of assessment of long term radon attenuation of covers has been demonstrated at Wismut [5]. The method is based on measuring the traces of lead (Pb-210) in the body of the tailings deposit and in the cover of the deposit.

The lead traces Pb (z) are estimated as the depth-dependent differences of the specific activities of Pb–210 and Ra–226 in the cover – tailings/waste rock profile:

$$Pb\,(z) = A_{Pb\text{-}210}(z) - A_{Ra\text{-}226}(z)$$

The method is primarily suitable for testing of covers older than 30 years. The basis of the method is the measurement of growth of Pb-210 ($t_{1/2}$ = 22 a) from Rn–222 ($t_{1/2}$ = 3,8 d), a daughter product of Ra–226 ($t_{1/2}$=1590 a), which are usually the main radioactive components in uranium tailings.

In a well sealing cover most of the radon decays into Pb–210 within a path length of 1 to 5 cm. The lead traces show discernibly positive values and the sum of the specific activities of the lead traces underneath and above the cover/mine waste interface gives a positive value. In a less well sealing cover, the positive lead traces in the cover are weak (little accumulation of Pb–210) and the lead traces in the tailings or waste rock are strongly negative due to weak attenuation of radon emanating toward the cover. The sum of the specific activities below and above the interface is negative.

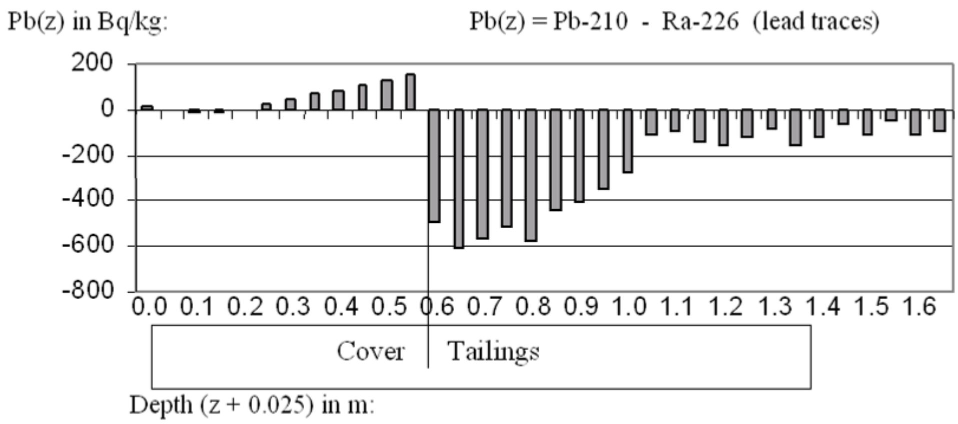

FIG. 4. Distribution of lead traces in a cover-tailings profile at Lengenfeld in the Ore Mountain. The construction of the cover dates back to the 1970s.

Figure 4 shows the performance of a tailings cover constructed more than 30 years ago. The cover was made of a single 50 cm thick sandy soil layer. The lead traces measured are clearly negative, evidencing that a 50 cm thick sandy soil cover is insufficient to provide adequate radon attenuation.

Remedial process

Unlike in regular civil engineering projects, the implementation of remedial works proved to be an iterative process with feedback loops rather than a linear succession of tasks, Figure 5.

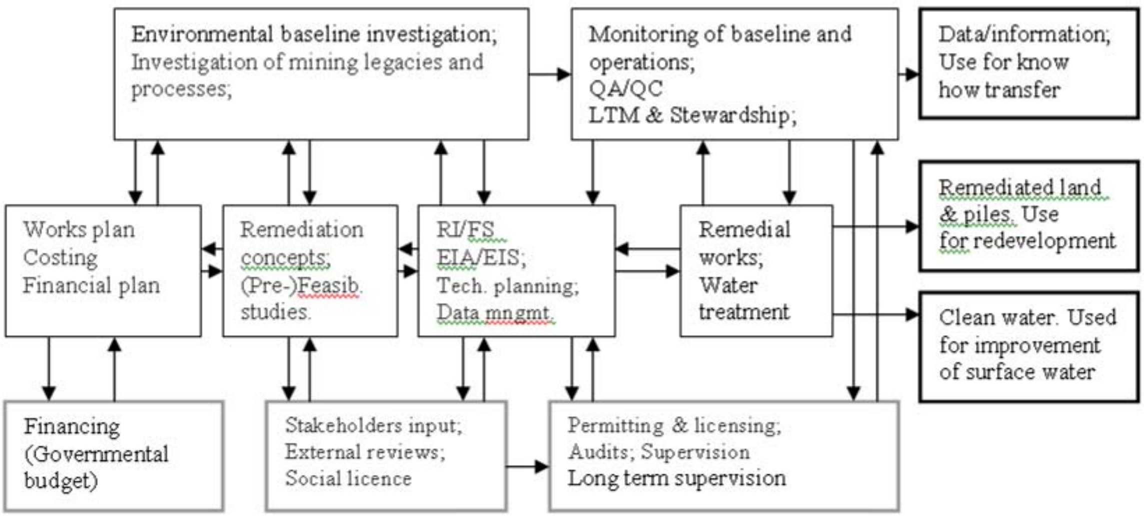

FIG. 5. The process, involvement of regulators and stakeholders and products of remediation.

Data Management

The reclamation workflow is managed by an SAP based interactive, process oriented system equipped with applications and tools sufficiently flexible to adjust to the changes occurring with the progress of remediation.

For data and information management an interactive, object oriented system has been created that makes the heterogeneous databases accessible corporate wide, while leaving maintenance and updating responsibilities at the data source level. The typical data/information content of the database comprises documents, photographs, object-related data, monitoring data, measurements and digital maps, geo-referenced aerial survey photographs etc.

Data transfer is realised through a web-based access to the “source” databanks with subsequent placement of the requested data in an object related (holding) databank on a central ORACLE server (Figure 6). This allows fast overviews, rapid applications, specific data quires to answer multifaceted questions that require overlaying of different types of data and information. Tasks, using locator and intersection functions for geometry-based data (polygons of sites, locations of measurement points), handled otherwise by GIS, can be easily accomplished using the capabilities of the databank. User’s access to a continuously updated GIS supported information system is provided at all times and the only requirement on the user side is internet explorer and fast internet access (DSL). Data safety is secured by applying very stringent criteria regarding inter-/intranet access.

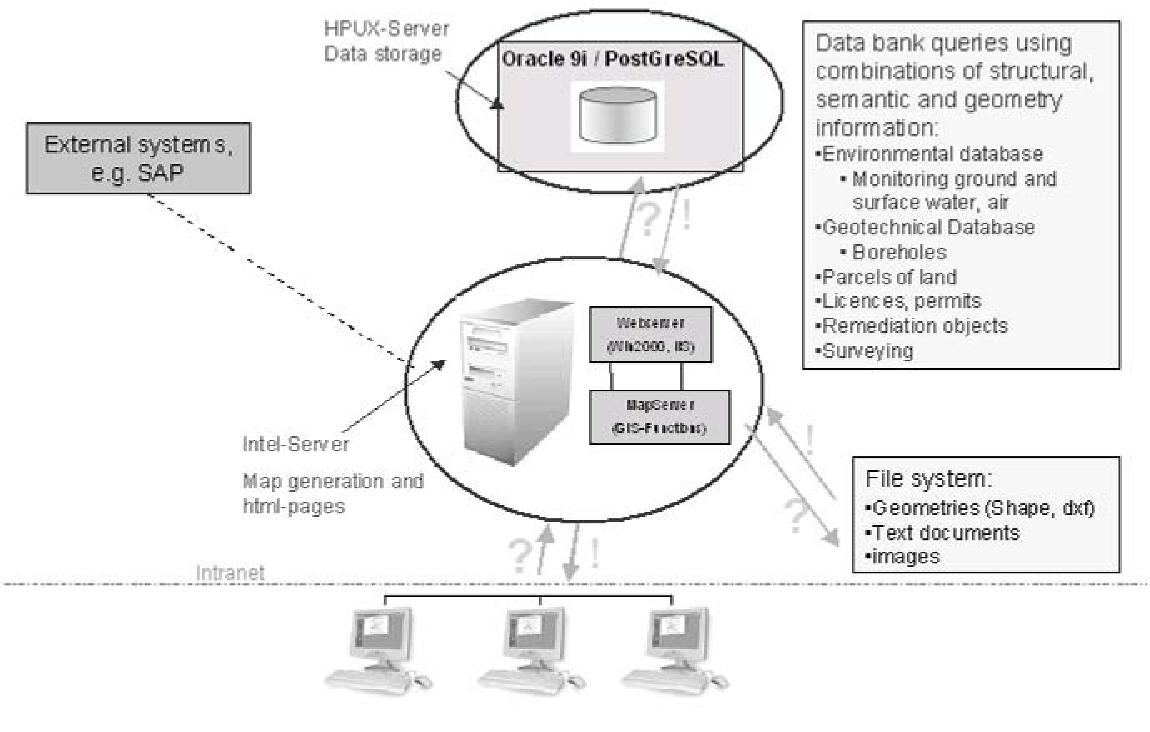

FIG. 6. Technical Data and Information management system used to integrate detached heterogeneous databases.

IMPLEMENTATION OF THE STANDARDIZED REMEDIAL WORK

In most cases, compliance with the legal requirements could be achieved by straightforward measures:

(a) excavation and relocation of contaminated materials, demolition of buildings and production facilities;
(b) reshaping of the remediated areas, waste rock piles and tailings deposits into stabile landforms having slopes resisting erosion and providing good surface runoff;
(c) covering of contaminated areas and sites to contain the health and environmental hazards and support vegetation; and
(d) treatment of seepages and discharges.

Contaminated areas

The remediation goal for contaminated areas was (whenever feasible) to maximize the extent of areas reclaimed for unrestricted use. This usually required a complete clean-up and a place to relocate the contaminated ground.

Waste rock piles

The practice of waste rock piles remediation was reshaping/stabilization and covering *in situ* or relocation to a central pile or into the closed-out open pit mine. At Ronneburg, the waste rock piles located close to the surface mine were used for backfilling of the open pit (1.6 by 0.9 km), which was approximately 180 m deep in 1995. The selected solution served both the remediation of the waste rock piles and the stabilization of the pit walls. The pyrite content was characteristically 0.5 to 7% and therefore the backfilling followed the strategy of placing the waste rock with the highest acid generating potential at the bottom of the pit into a zone, which will be below the ground water level after completion of flooding. This placement strategy prevented the oxidation of the acid generating minerals and the development of acidic seepage. Waste rock containing an overabundance of alkaline minerals was placed in the upper part (oxidation zone) of the pit [6] Figure 7.

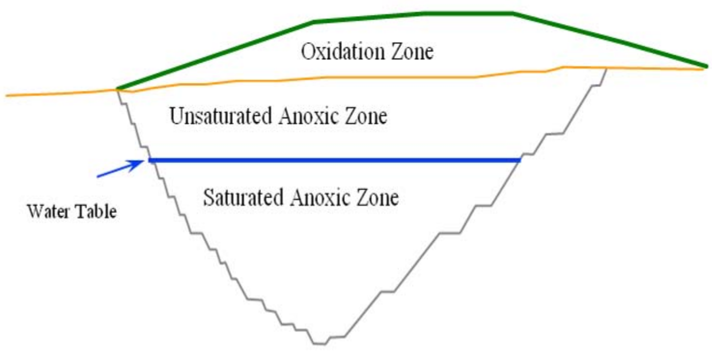

FIG.7. Backfilling strategy of the open pit mine at Ronneburg. Acid generating waste rock is placed in the saturated anoxic zone, waste rock of uncertain behavior in the unsaturated anoxic zone and non acid generating waste rock in the oxidation zone.

From 1990 till 2008 a total volume of 131 Mm^3 of waste rock (and related mine waste) has been placed into the pit. To handle such volumes of waste rock efficiently the largest fleet of Caterpillar equipment in Europe was put to work at Ronneburg. The annual volume relocated from 1996 to 2006 was approximately 10 Mm^3 at a rate of 40 000 m^3 of waste rock per day [4].

Tailings ponds

An overview of the most common technologies for stabilization of tailings and their limits are summarized in Figure 8 [7]. The ranges of applicability of a particular technology depend primarily on the state of consolidation of the tailings and are therefore, expressed in Figure 8 as a function of the *in situ* shear strength of the tailings. The state of consolidation of tailings depends on the local water balance of the tailings pond/deposit, i.e. on the climate. Accordingly, the approaches can differ substantially under humid and arid climatic conditions.

The tailings ponds of Wismut are reclaimed as "dry landforms". The sequence of measures to attain this goal is by (1) a step by step dewatering of the pond, (2) advancing an earth cover from the beach zones, (2) enhancing the dewatering of the soft tailings by using vertical drains and by placement of a thin earth cover (providing the first load) using light machinery and (3) by placement of an additional cover using heavy machinery after a sufficient shear strength of the tailings has been attained.

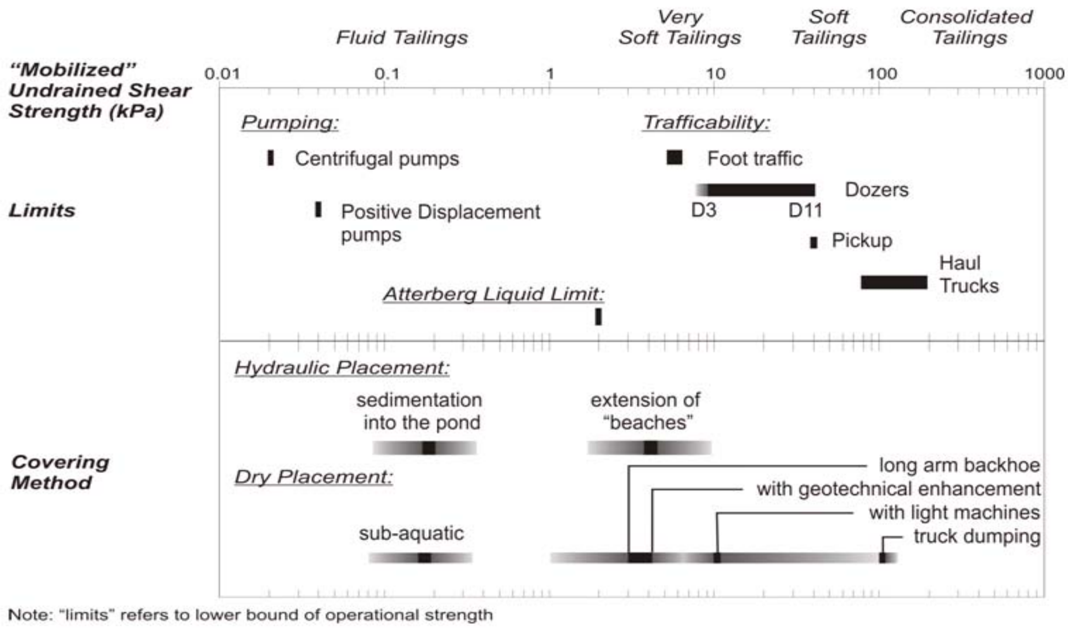

FIG. 8. Limits and ranges of safe trafficability of the tailings surface and feasibility of various tailings stabilization technologies in dependence from the in situ shear strength of the tailings.

Flooding of underground mines and water treatment

Mine flooding is performed in a controlled way to prevent contamination of surface water bodies and of aquifers suitable for water supply. Mine water discharges range from some 10 to 1250 m^3/h, depending on the size of the mine. Observations indicate that the initial peak load of contaminants in mine discharge decreases more or less exponentially over several years. Other discharges in need of treatment arise from dewatering of tailings ponds (several hundreds m^3/h) and from waste rock dump seepages (1 to 30 m^3/h). All discharges are treated and the water treatment residues (containing approximately 500 Bq/g) are disposed into waste rock piles and tailings ponds. After the peak load is over, the treatment requirements decrease radically as well, however often stay above tolerable levels of contamination. An overview of the mine water treatment approaches is given in [8].

Scrap metal

During remediation, considerable amounts of contaminated debris and scrap metals arise from demolition of buildings and production facilities. The contaminated metal components have a total alpha surface activity (TAA) in the range of mBq/cm^2 to Bq/cm^2 (of U–238 and its daughters). After demolition, contaminated and non-contaminated scrap metal usually ends up intermixed in unsorted heaps, typically showing a contamination distribution as presented in Figure 9.

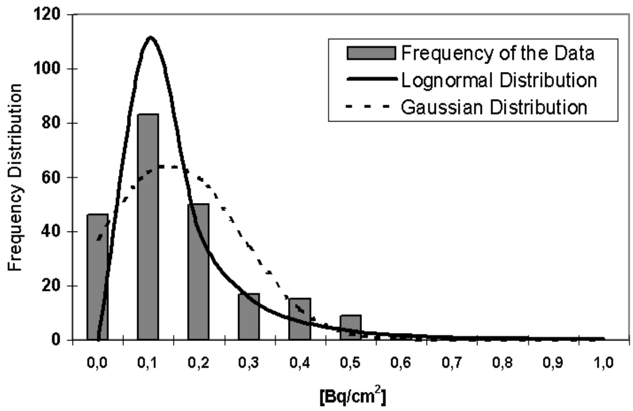

FIG. 9. Typical contamination frequency distribution of TAA values in a scrap metal heap at WISMUT.

The separation of the non-contaminated metal, which can be recycled, requires a reliable discrimination from the contaminated material. To improve selectivity without giving up using the standard portable, large surface (beta) contamination monitors in the field, a sophisticated method of calibration has been introduced. Based on the operational history of the particular facility and/or equipment dismantled, the level of contamination is pre-categorized and the anticipated nuclide vector and index nuclide established in the laboratory. Prior to the field campaign, the field instruments are calibrated against laboratory measurements of the specific waste type. Following this procedure, the estimation of TAA from the measured beta-count rates proved to be feasible with the required accuracy.

The decision regarding release or disposal of the scrap metal is based on the comparison of the TAA reference value (0.5 Bq/cm^2) with the upper limit of the confidence interval (95% confidence value) applicable to the particular contaminated scrap metal heap. The contaminated metal, which cannot be released, is disposed into the tailings, the backfill of the open pit or waste rock piles. Investigations demonstrated that the increase of the risk potential due to this metal disposal is marginal.

Monitoring of remedial operations

Monitoring of the ongoing remedial works is part of the radiation safety plan for protection of the workers, the general public and the environment exposed to the contaminants handled during the remedial works.

The monitoring was done by mobile units at places where the emissions arise and where impacts may be expected. The purpose was to see whether the regulated standards are observed and the contaminants releases do not cause an unacceptable radiological or chemical exposure.

The monitoring involved measurements of direct gamma radiation, critical radionuclides and critical chemical contaminants, Rn-exhalation rates, ambient dose equivalents, C_{pot}, Total Surface Alpha Activity and sometimes in situ -γ-spectrometry. The control of the flooding of mines and the establishment of hydrogeological parameters for modelling required over 1800 ground water observation points.

Great emphasis was placed on the measurement of dust emission that may contain long lived alpha emitters and toxic elements. Sprinkling (by water trucks) is applied routinely to prevent dusting at working places and construction roads during dry periods. To decrease discharges from the site and to economize water use, the water arising on the site is recycled within the site.

With the decrease of the remedial works the extent of the operational monitoring continuously decreased as well.

Monitoring of the environmental baseline

The monitoring program was designed for the control of intervention measures mitigating a pre-existing situation. Because no pre-mining baseline measurements were available, the monitoring program was developed on the basis of an initial characterization survey and predictive analysis of the exposure pathways.

The baseline monitoring network follows the level of gamma radiation, of contaminants typical for the Wismut sources and related parameters in surface and ground water, in seepage, in the air (particulates and radon), in soils and, in some instances in the human food chain.

The monitoring of the full extent of the legacies at the peak of the program required:

- 360 observation points along the water pathways (311 for water level, 107 for U_{nat} and Ra–226 and at selected points nuclide vector measurements);
- 337 observations points along the air/ground pathways (337 for Rn, 75 for dust and long-lived alphas and 81 points for Ra–226 in precipitated dust).

With progress of remediation the extent of monitoring and frequency of measurements were – in agreement with the regulator – continuously decreased. Particularly, the initial frequency of measurements could be decreased after the “behaviour” of the observed medium became familiar. During the phase of “standardized remedial works” the overly extensive monitoring network was scrutinized as well; the continued necessity of the measurement frequency and of each observation point –its change or relocation- was annually appraised.

It is expected that the post-remedial monitoring – after a remedial performance observation phase of several years – could be focused on monitoring of the key observation points only and make the frequency of measurements adjusted to the rate of natural processes, which are usually slow.

The monitoring data of Wismut reflect clearly the effects of the closure and flooding of the underground mines leading to an increase of contamination in the effluents, which started dropping immediately after construction of the water treatment plants (Figure 10).

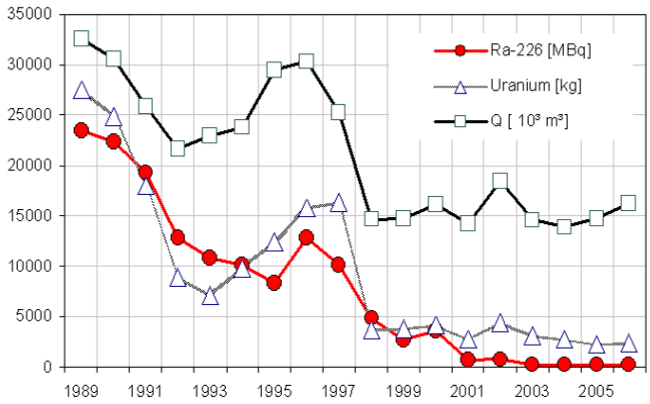

FIG. 10. Discharge Volumes and Uranium/Radium Load in the Wismut Effluents.

Beyond compliance with the environmental regulations the value added effect of the treated water discharge in the "Wismut" watersheds was that the receding and highly fluctuating water quantities in the small, local streams could be stabilized at an acceptable level and the environmental quality of the water in the streams considerably improved.

An overview of the monitoring approaches at Wismut and in various international monitoring programs is provided in [9].

REMEDIATION AS A PROMOTOR OF REGIONAL DEVELOPMENT AND INTERNATIONAL KNOW HOW PROVIDER

The most tangible results of the remediation effort are the reclaimed land and the stabilized and safely contained waste rock piles and tailings deposits. Based on the experience of external projects we concluded that both sustainability of the remediation results and post remedial stewardship are best guaranteed if the reclaimed land and remediated piles are put to productive use. This implied that beyond containment of health and environmental risks, the socio-economic effects of the remediation had to be included when defining the remediation goals. It was realised that value added results can be achieved at no additional (or at reimbursable) costs, if the future use of the reclaimed land /remediated piles has been specified prior to remediation in agreement with the future user, regulator and stakeholders.

Concerning utilization, there were no legal restrictions for completely clean-up areas. Neither was a problem finding interested parties for the cleaned up land. However, due to the high costs of a complete clean-up and to the relatively small risk associated with slightly contaminated areas most often only partial reclamations could be justified. In such cases, the recommendation of the German Commission on Radiation Protection (SSK-92, volume 23) restricts the post-remedial use to settlement of industry and trades.

The utilization of waste rock piles and tailings landforms is regulated by the "Ordinance for provision of radiation protection for waste rock dumps and industrial settlement ponds and for use of materials deposited therein (HaldAO)", which restricts the post-remedial use to forestation.

In line with the above regulation, most commonly forests and green fields were established on remediated piles. Undeniably, forestry has the advantage that it is sustainable use requiring little maintenance. Under the condition that the obligations regarding long term stewardship and stewardship (LTMS) can be met, exemptions to the restricted use were tolerated by the regulator in order to promote community development. By the way of exemptions, other, more "creative" uses became implemented such as, placement of solar panels on the remediated piles, using the plateau of the waste rock piles by the local community for recreational and sport activities or by the local club as a model plane airfield, etc. The economic incentive behind these uses is that they can at least partly pay for the costs of LTMS.

A model example of a sustainable (re-)development of a city was provided by Schlema in the Ore Mountains where the town development and remediation plans were very successfully coordinated. In 1990, a subsidence area of approximately 20 ha extended in the middle of the town and the surrounding countryside resembled a moonscape (Figure 11).

FIG. 11. Subsidence area in the city centre of Schlema before and after remediation.

FIG.12. The open pit mine in Ronneburg before remediation and prior to the BUGA 07 Exhibition.

The vision of the mayor of Schlema was to restore in town the former health spa, thus giving the town a post mining future. For his vision he mobilized the political support of the state government and the cooperation of Wismut within a realistic scope. By 1998, the park of the re-established health spa and the recreational facilities have been built on the stabilized subsidence area, followed by building of a promenade and of a golf course on top of the remediated waste rock piles (Figure 11).

The new post-remedial landscape (the valley of Gessen) next to the nearly remediated open pit mine in Ronneburg became an important part of the Federal Exhibition of

Landscaping and Horticulture (BUGA) in 2007, which was a national and international success (Figure 12). The BUGA 2007 exhibition provided important impulses for the future economic development of the former mining cities of Ronneburg and Gera.

The remediation sites in Schlema and Ronneburg became show cases proudly presented to the public by both Wismut and the communities involved.

Finally, of international significance is the experience and know how acquired during the Wismut remediation. This has been very successfully used in a number of countries helping to save the costs of their remediation projects while achieving remediation results of comparable quality [10].

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URANIUM ORE MINING AND THE REMEDIATION OF THE SITE IN HUNGARY

J. Banik, M. Csövári, G. Németh
MECSEK-ÖKÓ Zrt, Pécs, H 7633, Hungary

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Abstract

Uranium mining and processing had been developed in Hungary in the South part of the country in the Mecsek Hills, nearby county town Pecs. The uranium mining activities lasted from 1958 to 1997. Approximately 47 Mt of rock were mined, from which 7.2 Mt low-grade ore and 18.8 Mt of upgraded ore were processed. Two types of ore processing were used: alkaline heap leaching for low-grade ore and conventional acid leaching mill process for upgraded ore using acid leaching. Total uranium production was 20.8 Kt, including the uranium exported in the form of ore at the beginning. Remediation of the site started which is now near to its end. Most important post-remediation activity are the restoration of the groundwater quality in the vicinity of tailings ponds and mine water treatment aiming at the protection of the drinking water aquifer.

A brief overview of the former mining and processing activity, remediation activity and some lessons learned from them are discussed in the article.

INTRODUCTION

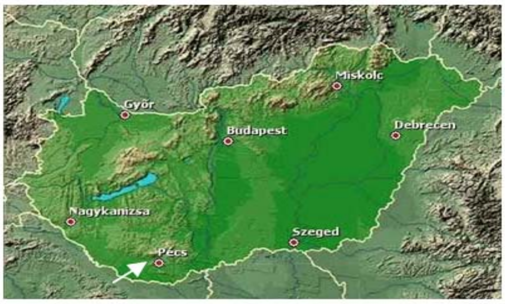
After promising preliminary results a detailed geological survey started in 1952, resulting in the discovery of the Mecsek uranium ore deposit. The deposit in the Mecsek Mts. is a sedimentary, terrestrial and river sandstone type deposit. The uranium carried by the water-flow got into the surrounding sediment via infiltration. Organic (carbonising) substances have a decisive role in the accumulation of uranium. The sandstone hosting the ore deposit is of the Upper-Permian age. The main ore minerals are uranium oxides, which belong to the uraninite-pitch blende-uranium soot series. The thickness of the productive formation is in the 5-120m range. The ore bodies are found in this sandstone in different layers and at several levels. Their size also varies i.e. they can be some meters or some tens of meters large (sometimes can even reach a few hundreds of meters) and their slips and slants can also be significantly different. Their average thickness is about 1 m and the range of difference alters between 0.3–0.5 m. The average quality of the deposit can be described as 0.13 U%, but the range within 0.03–3.0%. The quality range of the individual ore bodies is 0.06–0.35 U%.

Uranium ore mining activity started in 1958. At the beginning the upgraded ore was exported, later on in 1962 mill was built for the ore processing and from 1964 only yellow cake was exported up to the termination of the activity in 1997.

Altogether 26 Mt of uranium ore was chemically treated, from which 7.2 Mt low-grade ore were processed by alkaline heap leaching. 18.8 million tonnes were further upgraded to yellow cake by conventional acid mill process. The tailings of the mill process are stored on the tailings ponds the total area of which is 163 ha. The mass of the stored tailings is 20.3 Mt, with approx. 6.5 million m^3 of highly salty pore water. Because of the inadequate isolation of the tailings ponds and inadequate neutralization of the barren pulp during the operation of the mill, the groundwater is contaminated with chemicals (Mg, SO4, Cl, etc.) originated from the chemical ore treatment.

Remediation of the site is to be finished in the near future. Besides the long term monitoring the most important post-remediation activities are the extracting and treatment of the contaminated groundwater in the vicinity of tailings ponds as well the mine water treatment with the removing of the uranium in form of yellow cake.

The former uranium-mining site is situated on the south of Hungary, in the close vicinity of the town Pécs. The location of the site and the position of the main former sites on it are presented in the Figure 1. The most important peculiarity of the site is that it is situated very close to the drinking water catchment area therefore the protection of the groundwater quality is a very important task.



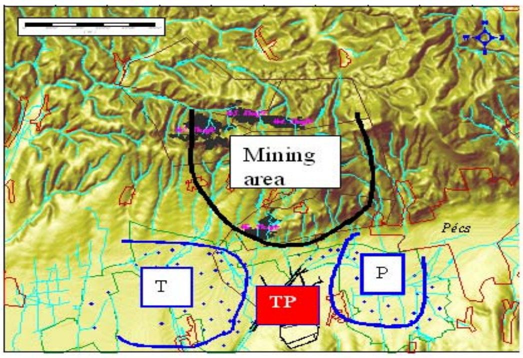


FIG. 1. Location of the uranium mining site. Tailings ponds (TP) are situated between the two drinking water catchment areas (T, P areas).

The proven *solid* ore resources on the site have been 39 Mt from which app. 20 Mt has been mined out. Mining and ore processing activity was terminated in 1997 because of the economical reasons. So there are still app. 19 Mt of solid ore on site but at the depth bellow 1000 m.

Reclamation work has been planned on the bases on international practice adaptation of which was supported by research and development programs of EU and the IAEA.

MINING AND ORE PROCESSING ACTIVITY

A detailed geological survey of the Mecsek uranium ore deposit was begun in 1952, as a result of which production was launched from 1955, first of all from test pits and exploratory galleries, then from the final facility on completion of the initiated investments. Mining production was launched in the southern forefront of the Mecsek range at depths close to the surface, and then continued in a northerly direction at increasingly greater depths. A total of 5 mine works were in operation, the last two working at depths exceeding 1000 metres.Mining production in the hard, highly rigid sandstone was based on drilling-explosion techniques.

The main production indices are shown in the following Table 1.

TABLE 1. MAIN PRODUCTION INDICES

Production	1954-1960	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	Total
Tunnel driving (m)	55.887	156.577	222.901	228.111	217.622	143.052	127.673	41.945	1.193.768
Total rock (m^3)	831.000	2.121.823	2.948.766	2.874.927	3.045.932	2.667.988	2.354.332	988.958	17.833.726
Total rock (t)	2.160.600	5.516.740	7.666.792	7.474.810	7.919.423	6.936.769	6.121.263	2.571.291	46.367.688
Ore (t)	975.224	3.244.082	3.827.360	4.107.930	4.199.242	3.695.160	3.441.697	1.911.677	25.402.372
Quality (U%)	0,104	0,089	0,071	0,076	0,082	0,074	0,080	0,106	0,081
Metal production (Ukg)	1.016.827	2.888.446	2.705.121	3.137.147	3.433.053	2.938.462	2.744.918	1.936.924	20.800.898
Underground exploring holes (m)	208.113	675.723	1.087.542	1.397.088	1.493.789	927.756	697.119	201.070	6.688.200

Mining and radiometric enrichment

The mining was very closly connected with the radiometric sorting and enrichment stations. The flow chart for the entire processing operayion is shown in Figure 2.

The first step of the radiometric upgrading was the radiometric sorting by bogie measuring station. The run-off mine ore was sorted into three classes: waste rocks (U<100 g/t), low-grade ore (U=100–300 g/t) and industrial-grade ore (U>300g/t). The next step was the crushing by jaw crusher to grain size <200mm. The broken ore was separated via sieves into five different fractions (200–140, 140–100, 100–75, 75–50 and –50mm) The ore fractions with grain sizes –50mm was directed to the mill and the other four fractions undergone radiometric sorting (piece by piece) on radiometric sorting machines. Doing this the volume of the rock to have been processed in the mill was reduced to 18.8 Mt.

The obtained concentrate together with the fraction – 50mm was processed in the mill, while some part of the reject (U>80 g/t) was crushed into grain size under 30 mm by cone crushers and processed by heap leaching together with the low-grade ore (see later). The rejects with low uranium content were placed on the central waste rock pile N3 (WP3)

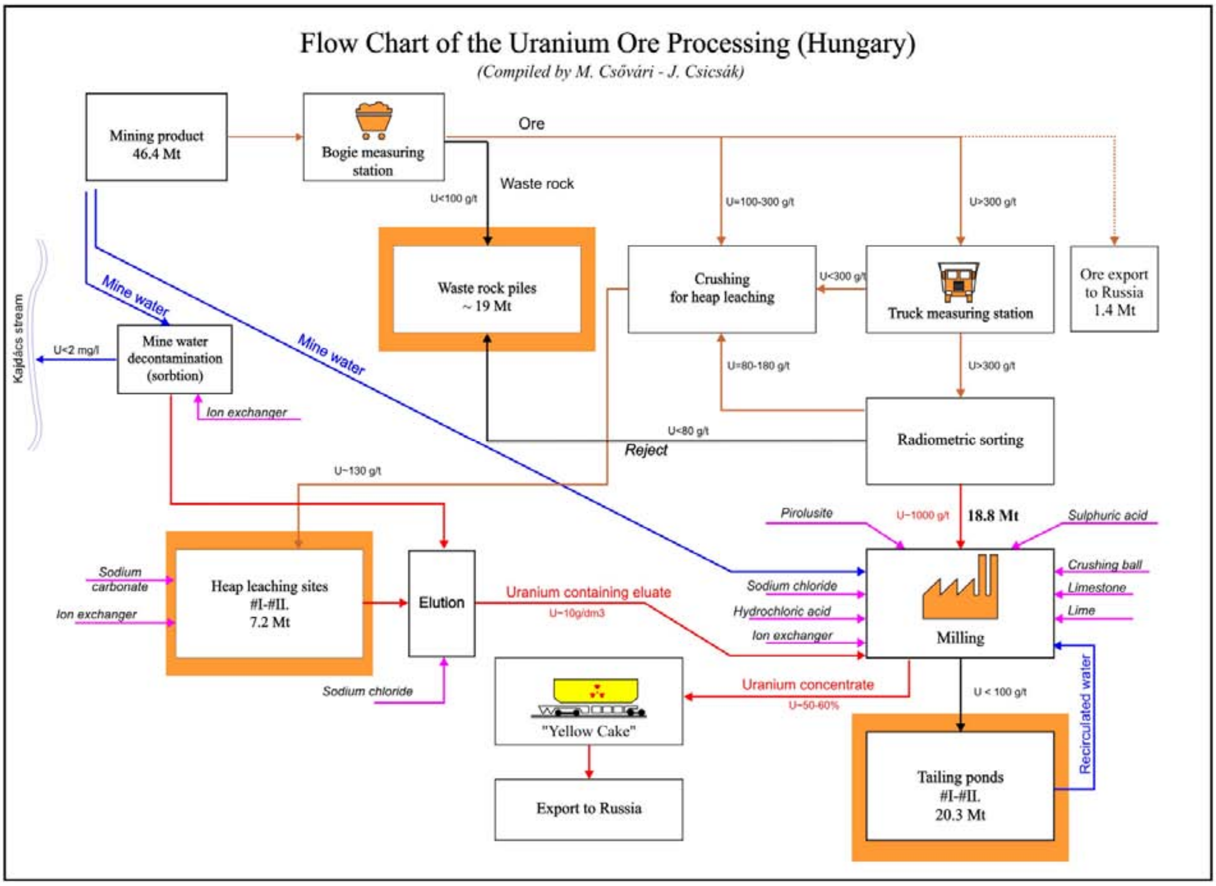


FIG. 2. Flow chart for uranium ore processing in Hungarian operations.

Milling

The upgraded uranium ore was fine- and medium crushed in the individual cone breakers, than milled in ball mills. Pyrolusite needed for oxidation was also fed into the mill.

The thickening of the pulp for leaching was carried out practically by cycloning while the Dorr-type thickener was operated just only as the buffer tank between the ball mills and hydricyclones (no polyelectrolite was used) giving four underflows (thickened pulp streams) for leaching. The four underflow fractions were gradually fed into the four-stage co-current leaching system, where the free acid concentration in the first reactor maintained on the level of 200 g/l. The acidity dropped gradually as the next pulp fractions were fed. In the last stage the free acid concentration was on the level of 10–15g/l. The acid consumption was rather high: app. 100 kg/t (at CO_2 ~3%) in the used leaching process, but the uranium recovery was as high as 95% even from the refractory ores containing branerite.

From the leached pulp the sand fraction was separated and washed on counter-current spiral classifiers. The leached uranium was removed from the slimy pulp with anion exchange resin. The loaded resin was eluated with sodium chloride + hydrochloric acid solution. The main part of the hydrochloric acid was produced in the eluation system converting the bond chloride on the ion exchanger into hydrochloric acid by treating it with sulfuric acid.

Uranium concentrate was precipitated from the eluate with lime milk. The barren pulp was neutralised in two stages: lime stone pulp was used in first stage (up to pH~3, and lime milk in the second stage (pH~7–7.5). The total specific consumption of the neutralising agents amounted to 31 kgCaO/t. Magnesium (leached from the ore) and partly the manganese (originated from the used oxidant, pyrolusite) ions did not precipitate at pH~7–7.5, therefore the liquid phase of the barren pulp had high TDS content. According to the calculations additional 10 kg CaO/t would have been used for the total precipitation of the magnesium and manganese ions. Because of the lack of the neutralising agent the tailings water were highly contaminated with magnesium sulfate (14 g/l) and the overall TDS (total dissolved solids) reached 22 g/l.

Alkaline heap leaching

The low-grade ore and partly rejects from radiometric enrichment (on this step app. 33% of rock mass was separated from the ore) was crushed to size <30mm and dumped on the leaching pads sealed with plastic foils in two layers. Approximately 300 Kt of broken ore was placed in every pad. Height of the heaps ranged between 10–13m. Most part of the process water was stored in the small basins shaped on the top of the piles. Sodium carbonate and bicarbonate solution (leaching agents) passed through the heaps [1]. The leached uranium was removed from the collected leachate by anion-exchange process. The barren solution was returned back on the top of the piles. The loaded resin was regenerated with sodium chloride + sodium carbonate solution. The regenerate (U~10g/l) was processed for yellow cake in the mill.

Using this process, 7.2 Mt of low-grade ore (U=136 g/t in average) was processed, removing 545 t uranium. Most part of the uranium has been leached in first three years (app. 45–50%). During the next 10 years the recovery was raising very slowly reaching app. 60% over 14 years. The specific consumption of the sodium carbonate for leaching was 5 kg/t.

The alkaline heap leaching was carried out on two sites with total area of app. 47 ha (Figure 3). Using expanding pads the specific land need was approxim. 6.8 ha/Mt. It should be underlined that the process was used first of all from the environmental protection point of view for removing of the easily leachable part of uranium from the under-grade ores (wastes). This is why the relatively low recovery percentage was acceptable.

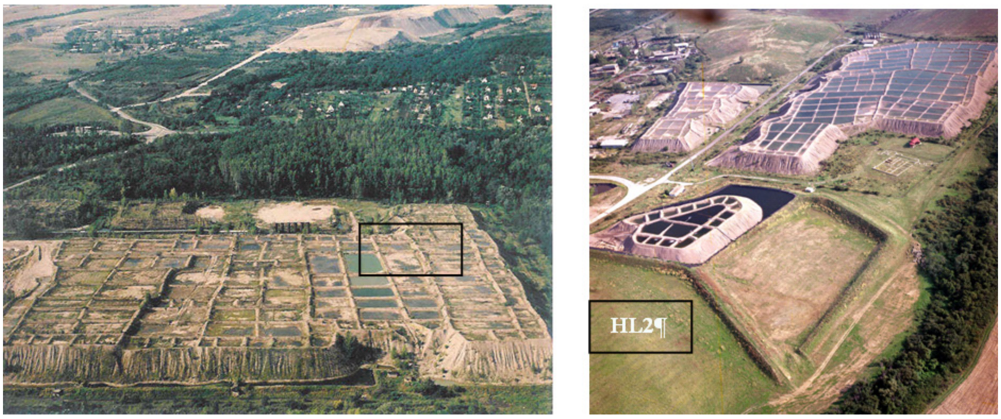


FIG. 3. Views of heap leaching site.

MINE CLOSURE AND RECLAMATION

In April 1997, the Hungarian Government decided to shut down uranium ore mining in the Mecsek and to carry out mine closures, landscaping and environmental protection measures in the sphere of enhanced state responsibility. The decision was founded on a study of environmental effects, as well as an investment plan produced on this basis, which envisaged a complete elimination of the environmental damage resulting from the Hungarian uranium ore mining and ore processing operations [2, 3]. An assessment of the liabilities for the remediation was carried out (Table 2).

The total cost foreseen for the scheme was 100 million USD; the original planned deadline has been modified three times due to financing problems. The present deadline for completion is 31 December 2008, which can be met if financing conditions can be covered. The actual total expected costs, in spite of the significant delay (6 years), will only exceed those forecasted by around 10%.

TABLE 2. INVENTORY OF THE LIABILITIES

Underground Voids

Cavity capacity Mm^3	Mined rock Mt	Pumped mine water Mm^3	U production Fmetal U Et
17.9	46.4	69.8	20.8

Industrial Areas, Roads

Total area ha	Contaminated with radioactive components	Contaminated with oil	Chemical contamination
216	44	0.3	0.6

Waste-rock Piles

Facility	Area	Disposed material	Average content of radioactive component	
piece	ha	Mm^3	U_{term} g/t	^{226}Ra Bq/g
9	82.5	9.9	20-70	0.3-1.6

Heap-leaching Areas

Facility	Area	Disposed material	Average content of radioactive component	
piece	ha	Mm^3	U_{term} g/t	^{226}Ra Bq/g
2	47	3.4	60-70	1.5-2.0

Tailings Ponds

Facility	Area	Disposed material	Disposed tech. solution	Average content of radioactive component	
piece	ha	Mt	Mm^3	U_{term} g/t	^{226}Ra Bq/g
2	163	20.4	32	60-70	~12.5

Reclamation works were carried out on the bases of the environmental license issued by the local Environmental Protection Agency. The some most important limits to be met during the remediation are listed in the Table 3.

TABLE 3. LIMITS FOR RADIONUCLIDES

Objects, parameters	Limits
Waste rock piles, heap leaching, tailings ponds, ore dumps, etc.	
Radon exhalation, Bq/m^2s	0.74
Radon concentration in the air, Bq/m^3	Background + 20
Gamma-dose rate, nGy/h	Background + 200
Specific activity of the soil, Bq/kg	
In the upper 15 cm	Background + 180
In the following 15 cm layer	Background + 550
Surface facilities, buildings and their immediate surroundings	
Inside buildings	
Radon concentration in the air, Bq/m^3	Background + 30
Gamma-dose rate, nGy/h	Background + 200
Bound surface alpha-activity, Bq/cm^2	

The contaminated earth, debris from decommissioning and highly contaminated equipment (tanks, pumps, etc.) has been placed on the waste disposal area created on WP3.

Closing of mines and underground facilities

In the course of mine closure, contaminated equipment has been dismantled and removed. Organic-contaminated rock was removed and microbiologically treated on the surface (approxim. 3500 m^3). Fuel and other pollutants have been eliminated too. Rock tension was released by ripping in the excavations in order to avoid possible mine quakes in the future. The necessary barriers to divert and block water and air have been installed, and the open shafts, including 5 deep shafts (1000 m each). Following this, flooding of the mine with water was begun.

Reclamation of surface facilities

The reclamation of surface facilities has been carried out in such a way that these should not need aftercare and they should be suitable for carrying out industrial activities of other kinds whilst conforming to radiological and other environmental protection requirements. This has involved the removal of around 700 000 m^3 of primarily radiologically polluted soil from a total area of 216 ha, which was replaced with around 500 000 m^3 of inactive soil. As a result of the cleanup, a significant portion of the former works territories is suitable for reuse without restriction.It should be mentioned that the inactive earth (loess) for covering was mined from the quary opened on the unused hill-type TP2 territory.

Reclamation of the waste rock piles and their surroundings

Stabilization of the waste rock piles has been achieved by adapting them morphologically to the landscape; dust and radon emissions have been reduced to below the permitted limiting values by covering with soil. Binding of the covering layer and prevention of erosion has been ensured by planting vegetation (designed for minimal maintenance requirements), run waters have been collected and treated.

This task has involved the placing of around 20 Mt of waste rock (U~ 60–70g/t on the average), partly on site, partly on the WP3 and covering with a 1 m layer of inactive soil.

For disposal of the sludge from water treatment process and some other wastes a waste storage area is being operated on the pile. Position of the WP3 is very favorable for waste disposal because the main part of the drained (through the pile) water is collected in the underground voids of mine N1 situated under the WP3. For the decreasing of the uranium concentration in groundwater leaving the site through the narrow *Zsid-valley* experimental permeable reactive barrier (PRB) has been built in the frame of PEREBAR project financed by the EU. The areal view on the WP3 and the location of the PRB is presented in Figure 4 [4].

FIG. 4. View on WP3 and the location of the PRB.

Reclamation of the heap leaching sites

All residues from heap leaching (~7.2 Mt) containing 50–70 g/t of U, representing a danger to the surrounding drinking water base, have been relocated to the WP3, and placed there together with the waste. On this site, an area of 47ha, decontamination, water management and grassing has been carried out. This is a suitable area for reuse as a potential industrial site. Areal view on the revegetated former heap leaching sites is presented in Fiigure 5.

Some GW pollution is detected in some spots, which is to be eliminated by extracting with wells and treating.

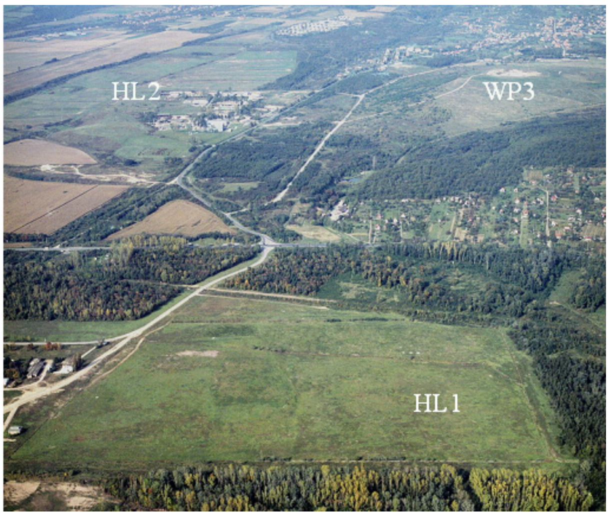


FIG. 5. View on the remediated heap leaching sites and WP3.

Mine water treatment

The mining activity in the past lead to the opening 5 shaft, one near surface (Southern shaft) and the others at depth of some hundred metres (northern shafts). During the mining app. 64 million m^3 of mine water were removed previously used in the mill process, treated if needed and discharged. Presently the deep mines are under flooding, while the water from near-surface shaft (shaft N1) is being pumped for maintaining a depression funnel to avoid escape of the uranium contaminated water in the direction of the drinking water aquifer.

The uranium content of mine water is 4–5 mg/l. Uranium has been removed by anion exchange process after all, in the form of commercial-grade uranium peroxide. Uranium concentration in treated water is <0.2 mg/l (discharge limit is 2 mg/l). Detailed information on mine water treatment is disclosed in other publications [4–6].

Reclamation of the tailings ponds and their surroundings

This has been the greatest task for reclamation, consuming around 40% of the total expenditure for the reclamation. This work has involved finding a solution for the final disposal of approx. 20 Mt of chemically treated residues with 50–70 g/t U content, app. 6.5 million m^3 of contaminated tailings water [4, 7]. Tailings are stored in two tailings ponds with a total area of 163 ha.

Important steps in the reclamation of the tailings ponds are:

- detail investigation of the soil mechanical charasteristics of the tailings;
- treatment and discharge of the stored free water;
- establishment of morphology with relocation suitable for regulated collection of precipitation water;
- reconstruction of belt ditch and drainage channel system, and a separate dich for collecting run-off;
- construction of special multilayer (sandwich-structure) cover, to reduce the emission of radon gas and the infiltration rate; and
- establishment and operation of an active water restoration system for decontaminating the territory around the TP area contaminated by 40 years of leakage of highly polluted tailings water, in order to ensure the safety of the surrounding drinking water aquifer.

The first step was the discharge of the free water (after its treatment for removing the radium and decreasing the TDS). This step was followed by the desiccation of the fine tailings zone resulting in a though weak, but solid surface (Figure 6). One of the most complex tasks was the further stabilization of this weak fine tailings zone. This was achieved by dewatering the soft tailings using geomaterials for supporting the *loading sandy tailings relocated from the dam*. The method used is based on the international experience of the stabilization of soft tailings [8–10]. For enhancing the process of dewatering in critical zones (from the point of view of the further remediation work) additionally a horizontal deep drainage was built crossing the dam, transition zones and partly the fine tailings zones [11]. In Figure 7 the principal equipment and the location of the horizontal drainage are presented. The drainage allowed removing additional water from the effected tailings zone.

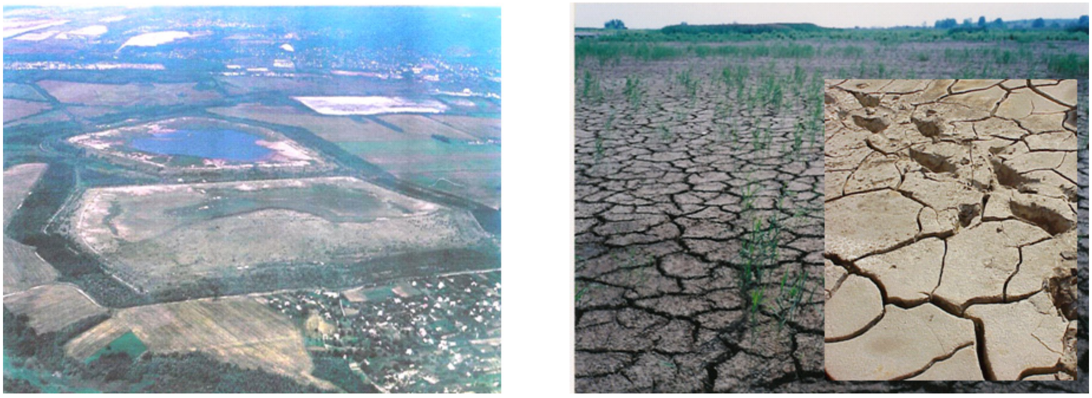


FIG. 6. Free water on the tailings ponds and the desiccation of the slime zone.

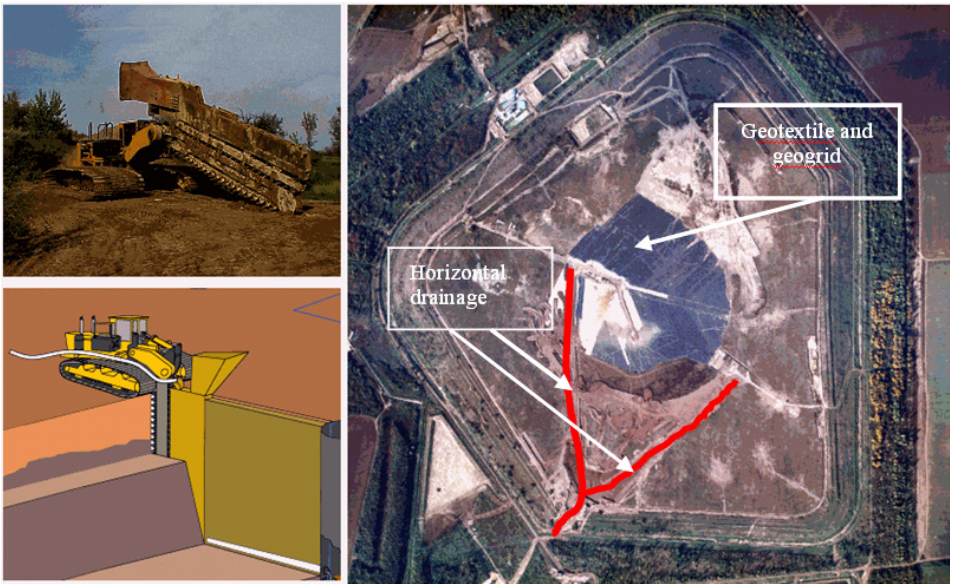


FIG. 7. Construction of the horizontal drainage in transition zone.

The cover design was selected on the basis of modeling of the water balance. According to the calculations (HELP model) the required thickness of the cover (for reducing the infiltration rate to the acceptable level of 40 mm/y) is 1.5 m, including 0.3 m clay sealing layer and 0.3 m compacted protection loess layer. Such cover can decrease also the radon exhalation rate below the limit value of 0.74 Bq/m^2s.

Altogether approx. 2.5 million m^3 of earth (loess, clay and sand) will have been used for covering the tailings piles. Most of this quantity (approx.1.8 million m^3 loess) has been excavated from the quarry opened on the unused TP2 territory. Such cover can also decrease the radon exhalation rate below the limit value of 0.74 Bq/m^2s. The remediation of the tailings ponds is near to its end; it will be finished most likely in 2008.

It should be mentioned that sometimes during heavy rains the cover were seriously damaged by water erosion. This problem exists up to the strengthening of the vegetation on the surface.

The remediated piles are used as a sheep-run (Figure.8).

FIG. 8. Stabilization of the fine tailings zone on tailings pond and view on the remediated and revegetated tailings pile.

It is expected that the additional dose rate for the public living in the vicinity of the tailings ponds will be decreased much below 1 mSv/y.

Groundwater restoration

The groundwater (GW) around the tailings ponds is highly contaminated with magnesium sulfate, sodium chloride, etc. To protect the nearby drinking water catchment area a water quality restoration facility is being operated on the site. The facility consists of drainage and water extracting wells, as well as the water treatment station. The layout of the wells and drainage are presented in the Figure 9.

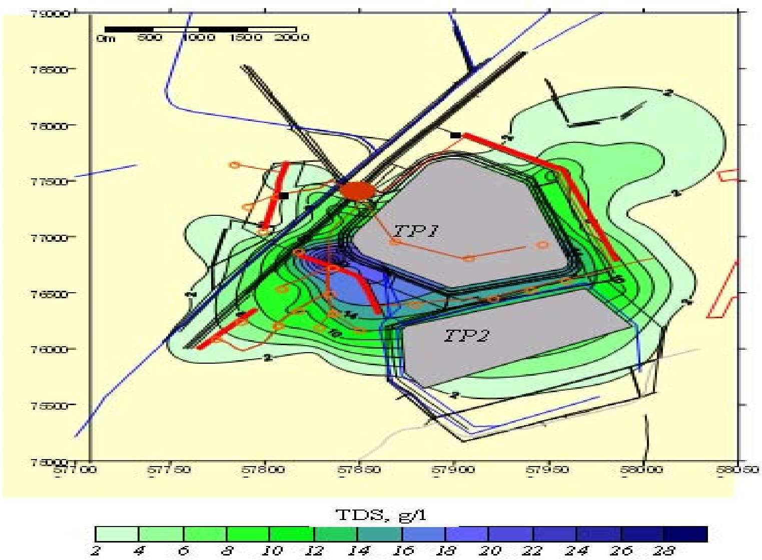


FIG. 9. Location of the groundwater extracting wells and drainage and the extension of the contamination in shallow GW (26 wells,   3.1 km long drainage placed at depth of 6-9 m).

The volume of the yearly extracted GW is on the level of 0.5–0.7 million m^3. The TDS of water depends on the depth of extracting: in the case of shallow GW it is approx. 13 g/l, while that extracted from the deeper levels is app. 3–5 g/l. Main pollutants are magnesium, sodium, sulfate and chloride. The extracted shallow GW together with the seepage water collected by the belt ditch is treated with lime milk precipitating magnesium hydroxide and gypsum. The sludge is thickened, filtered and transported on the WP3 to the waste disposal area. The yearly quantity of the sludge is 3–4 Kt (dry). The treated water is mixed with treated mine water and discharged.

LONG-TERM MEASURES

Following the main afterclosing measures are planned on the remediated site:

- continuous operation of the established radiological-hydrogeological-geodynamic monitoring system; planning and implementation of technical intervention to be carried out if necessary;
- continuation of the GW restoration around the tailings ponds and mine water treatment;
- maintenance of belt ditches and drainage channels, repair of erosion damage of the reclaimed surfaces of tailings piles and waste rock piles (approxim. 300 ha).

LESSONS LEARNED FROM THE REMEDIATION

The main lessons are as follows:

- During the backfilling of the 1000 m deep ventilation shaft N5 it became necessary to interrupt the hydraulic connection between the karstic and the contaminated deeper aquifer on 400m depth. This was achieved by plugging a 50m thick zone and injecting cement pulp into the rock around the plug. The method used proved to be very effective.
- It is strongly believed that the radiometric sorting and upgrading method used, proved to be a very effective instrument for improving the economy of the ore processing.
- In the case of opening a new facility, further improvement of the efficiency of the radiometric methods could be achieved by placing the radiometric stations directly into the mine leaving the separated wastes and rejects in the mining area for backfilling. *By this way the volume of the wastes to be deposited on the surface could be reduced in large scale. This would result in significant reduction of the remediation cost and pollution of the environment as well the long term post remediation cost for monitoring and aftercare of the waste rock piles***.** Additionally the treatment of low-grade ore on the surface could be eliminated.
- In respect of the heap leaching it should be taken into account, that the GW contamination was found first of all along the pipelines and pumping stations. For decreasing the land needed for heaps instead of expanding pads, permanent pads could be recommended.
- Neutralization of the barren pulp discharged into the tailings ponds must be neutralised to the pH ensuring full precipitation of the magnesium ions to avoid the high TDS-containing tailings water on the site.
- Stabilization of the transition zones can be effectively enhanced by having deep horizontal drainage.
- The tailings ponds must be isolated effectively from the soil to avoid the GW contamination with tailings water. Lack of appropriate isolation can lead to the high GW contamination, needing long term water quality restoration work on the site.

- To decrease the water erosion of the cover systems on tailings ponds, appropriate diverting cross ditches have to be built on the surface.

CONCLUSIONS

If the long term measures are implemented with care, the reclamation mine-closure work carried out will ensure that the pollution will disappear on the territory affected by more than 40 years of uranium mining, the ecological balance will be restored, and a significant portion of the former uranium mining area can be reused for other purposes.

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URANIUM MINING AND REMEDIATION IN INDIA©

A. Chaki
Atomic Minerals Directorate for Exploration and Research, Government of India

Paper invited by UMREG in 2007

Abstract

The paper describes the present situation of uranium mining and remediation in India.

INTRODUCTION

In India, the nuclear energy sector encompassing the complete fuel cycle is under the control of Department of Atomic Energy, Government of India. Uranium Corporation of India Ltd. (UCIL), a public sector undertaking under Department of Atomic Energy, with its headquarter at Jaduguda has been operating four underground mines, one opencast mine and two ore processing plants in East Singhbhum district of Jharkhand state. All these units are located in a geologically significant province – called Singhbhum Shear Zone, known for its uranium-copper resources. In addition, two large uranium mining and processing projects have been planned in the States of Andhra Pradesh and Meghalaya. These mines will be brought into production during the period between 2007 and 2012, and thereby increase the uranium production in the country for India's nuclear power programme. Though the mining operations for uranium in India commenced way back in the year 1968, no uranium mine has been closed so far in India.

Uranium Exploration in India

Atomic Minerals Directorate for Exploration and Research (AMD), Department of Atomic Energy, Government of India is the only agency engaged in the uranium exploration in India. Uranium exploration in India dates back from late fifties and the first uranium deposit (vein type) was discovered at Jaduguda in 1951 in the Singhbhum Shear Zone (SSZ), Jharkhand state. Subsequently, over a period of fifty years, a number of low grade small to medium size uranium deposits all along SSZ were discovered and some of them were pressed into production. In the meantime, in other parts of the country, a number of new uranium deposits were discovered viz. Umra (vein type), Rajasthan; Tummalapalle (dolostone hosted, strata-bound), Andhra Pradesh; Domiasiat-Wahkyn-Tyrnai-Gomaghat (Cretaceous sandstone type), Meghalaya; Bodal-Jajawal (vein type), Chhattisgarh; Lambapur-Peddagattu-Chitrial-Koppunuru (unconformity type), Andhra Pradesh; Rohil (metasomatite), Rajasthan; Gogi (vein type), Karnataka and a number of smaller deposits spreading across India. AMD has so far established a total of 107 268 tonnes of U_3O_8. AMD is one of the early leaders in airborne gamma ray surveys for uranium exploration and the first airborne total count Gamma ray surveys was carried out in the year 1955. Subsequently AMD has covered over 500,000 line Km of airborne gamma ray surveys, mostly gamma ray spectrometric, across the country. Over the years, for uranium exploration, AMD has followed the strategy of airborne Gamma

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ray and magnetic surveys followed by regional geochemical and radiometric surveys for the identification of potential uraniferous provinces. Subsequently a detailed geological, geophysical and radiometric surveys followed by subsurface exploration campaign ensures the discovery of uranium deposits. In order to successfully carry out the uranium exploration programme, AMD has a strong human resource base of geologists, geophycists, chemists, nuclear phycists, drilling engineers and support staff and state of the art support laboratories.

Apart from the Singhbhum Shear Zone, potential for uranium mineralization has been recognized in three other important geological environments viz.

(1) Fourteen Proterozoic basins for unconformity related and stratabound deposits,

(2) Createceous Mahadek sediments of Meghalaya state for sandstone type uranium mineralization, and

(3) North Delhi fold belt of Rajasthan state for Na-Metasomatite type mineralization.

After the discovery of an unconformity type uranium deposit in the Proterozoic Cuddapah basin in Lambapur, Andhra Pradesh, the possibility of finding similar deposits in analogous geological environments around the country was realised and huge exploration inputs have been deployed in seven of the fourteen basins in the country. The fourteen basins occupy an area of 225,000 sq.km and dispersed in the peninsular India. Most of the exploration inputs for unconformity type uranium deposits so far have been in the shallow fringe areas of the basins and a number of small to medium sized uranium deposits have been established in some of the basins entirely based on leads provided by mineralization in surface outcrops. With the advent and success of Frequency Domain Electro Magnetic and Time Domain Electro Magnetic surveys in other parts of the world, AMD formulated a strategy to carry out nearly 400,000 line Km of airborne Time Domain electromagnetic surveys (with radiometric and magnetic) in many of the potential areas in the country including the Proterozoic basins. AMD has also plans to infuse vast ground geophysical inputs for the immediate exploration programme.

1.1. Operating mines

Spanning over a period of forty years, UCIL have established their units in East Singhbhum district of Jharkhand state, in line with the requirements of uranium for India's nuclear power programme. A brief description of the operating uranium mines and ore beneficiation plants is given below [1].

Jaduguda Mine

Commissioned in 1968, it is the first uranium mine in India to produce uranium ore on a commercial scale and is in continuous operation since then. Initially this mine was developed upto a depth of 315 m with a 5m dia vertical shaft as entry into the mine. Later on, the mine was deepened upto 640 m. Further deepening of Jaduguda mine was taken up by sinking a vertical shaft from a depth of 555 m to 905 m. This new shaft was commissioned during 2002. Now most of the mining activities at Jaduguda are carried out below 600 m depth. Cut-and-fill is the principle stoping method followed at Jaduguda. Deslimed mill tailing is used as the fill material. Various modifications and standardisation with regard to roof supporting, stoping methods, machinery utilization, stowing etc. have been fine tuned for better recovery of ore. Jaduguda is the deepest operating underground mine of the country with intrinsic deep-mining concerns like ventilation, strata control, rock temperature etc.

Bhatin Mine

It is a small uranium mine situated 3 km west of Jaduguda. Geological settings and other host rock characteristics in Bhatin are similar to Jadugdua deposit. This mine was commissioned in 1986. The entry to Bhatin mine is through an adit driven at ground elevation. Two principal winzes have been sunk up to 135 m below surface. Cut-and-fill is the principal stopping method. The mine is now 185 m deep. Further deepening up to a depth of 230 m has been taken up to create additional production levels. The mine has limited indicated reserves only up to a depth of 250 m.

Narwapahar Mine

It is located 12 km west of Jaduguda. It was commissioned in 1995 and rated as one of the most modern underground mines in India. A 7^0 decline has been developed as an entry to the mine through which large machinery could move and operate underground. From the decline, ramps are developed as entry to the slopes at different elevations. This enables free movement of large trackless mining machineries like twin-boom drill jumbo, low-profile-dump-truck, service truck, passenger carrier, low profile grader, scissor-lift etc. into the mine. Innovative new technologies have enabled early commissioning of the mine with high productivity and low mining cost. Cut-and-fill is the principal stoping method adopted in Narwapahar mine. The deslimed mill tailings of Jaduguda mill along with the waste generated from the mine are used as the filling material. Hoisting of ore from deeper levels is done through a vertical shaft sunk upto a depth of 355 m.

Turamdih mine

Turamdih uranium deposit is located about 24 km west of Jaduguda. This mine was commissioned in 2003. The entry into the mine is through a 8 degree decline which provides facilities for deployment of trackless mining equipment like passenger carrier, drill jumbo, low-profile dump truck etc. At a depth of 70m, the orebody has been accessed from the decline by a cross-cut. Decline has also been extended up to a depth of 110 m. Drives are being developed following the contacts of orebody. A vertical shaft of 5m diameter is being sunk from surface upto a depth 250 m with services for ore hoisting and movement of men and material. Production capacity of this mine is now being enhanced from 750 TPD to 1000 TPD.

Banduhuran mine

It is the first opencast uranium mine in the country put into production in June 2007. Situated adjacent to Turamdih underground mine, the low grade deposit contains a moderate reserve of uranium. It is now a conventional opencast mine using excavator-dumper combination maintaining ore benches of 6m height. The pit will attain the ultimate depth of 160m with ore to overburden ratio of 1:2.7. Ultimate pit slope has been designed for 47^0 up to a depth of 120 m and 44^0 below 120 m. Production capacity of this mine is now being expanded from 2400 TPD to 3500 TPD.

Operating ore beneficiation plants

Jaduguda plant

The plant was commissioned in 1968 with a capacity to treat 1000 tonne of dry ore per day. In Jaduguda mill, the ore is ground in three stages to the stage of the slurry. The slurry is thickened and leached in leaching pachucas under controlled pH and temperature conditions. The leached liquor is then filtered and made to undergo ion-exchange in which uranyl ions get absorbed in the resin. This is further eluted and treated with magnesia to get magnesium diuranate or yellow cake.

With the commissioning of Bhatin mine during 1986, the processing capacity of Jaduguda plant was expanded. The capacity was further expanded after commissioning of Narwapahar mine. Presently, Jaduguda plant treats 2090 tonnes of ore per day. The plant has also undergone several modifications adopting technologies to maximize the re-use of water, high recovery of the product and minimum discharge of effluents. It has several automated process control mechanisms and on-line monitoring systems. Capacity of this plant is now being further expanded to 2500 TPD.

Turamdih plant

A new plant at Turamdih with a processing capacity of 3000 tonnes per day has been set up (cold commissioned in June 2007) to treat the ore produced from Turamdih and Banduhurang mines. The flowsheet of this plant is similar to that of Jaduguda. However, taking account of new developments in hydrometallurgy / processing technology worldwide, some efficient equipment like apron feeders, particle size monitors, horizontal belt filter, pressure filter etc have been incorporated in this plant. In order to minimize the human interference, a high degree automation and instrumentation have been instituted. PLC based control system based on Man–Machine Interface (MMI) with remote input – output and facility to monitor process parameters, status of drives, control of relevant process variables and operate any equipment from plant graphics on operators' station have been implemented. Expansion of Turamdih plant to 4500 TPD processing capacity is being taken up to accommodate the ore produced from another new mine at Mahuldih, expanded capacity of Banduhurang and Turamdih mines.

WASTE MANAGEMENT

Most of the waste rocks generated in the mining of uranium ore are disposed of underground for filling the void created by excavation of ore. The mine water is reclaimed for use in ore processing plant after clarification. The mill tailings form the bulk of the waste generated. The coarser fraction of the tailings (about 50%) after neutralization, are used in underground for filling the mined out stopes. The fine fraction in the form of slime, are neutralized and disposed off in a specially engineered tailings pond which has high natural hills as barriers on three sides. The embankment has been designed in one side to accommodate the entire tailings for a very long period with no scope of discharge into the environment. The decantation wells in the pond are in place for preventing any discharge of solid particles. The decanted effluent from the tailings pond is treated further at effluent treatment plant and is brought to normal conditions before being used in the process. Remaining water, if any, is discharged into the local stream after confirming to standards set by the Atomic Energy Regulatory Board, India and the IAEA. Access to tailings pond area is prohibited and security personnel are posted at site as guard against any entry. The pond is located at a safe distance from the population to avoid any direct contamination. A large part of the tailings pond is covered with vegetation to prohibit re-suspension of dust into the atmosphere [2].

During the last 36 years of operation of mining and processing of low-grade uranium ore, UCIL has always maintained a very high level of safety, health and environmental standards in conformity with the international practices in the nuclear industry. The guidelines of different regulatory bodies like the Directorate General of Mines Safety, the Atomic Energy Regulatory Board, the State Pollution Control Board and the Ministry of Environment and Forest, the IAEA, etc. are strictly adhered to.

Monitoring of bore wells at tailings pond

Sets of 16 bore-wells each extending to a depth of about 20–22 m reaching up to the hard bed rock have been constructed parallel to the dam axis of the I and III stage tailings pond respectively. These bore-wells are at a distance of 100 to 200 m away from the embankment in the direction of natural drainage.

Effluent and aquatic monitoring (Jaduguda)

A major portion of the effluent obtained from mine, mill and tailing ponds are collected, clarified and recycled for use in the process line. Effluents from plants and those released from the Effluent Treatment Plant to the local aquatic system are continuously monitored.

Mine water from Jaduguda is recycled for use in mill and that from Bhatin is sent to the water treatment plant for use as industrial water or discharged after treatment. Narwapahar mine water is also brought to ETP for recycling and treatment before discharge.

Mine water effluent from Narwapahar

The liquid effluents from Narwapahar mine are stored in the effluent storage pond and are regularly analysed for dissolved radionuclides and chemical toxins. Results from recently conducted chemical analyses of dissolved cations and radionuclides are given in the table below (Table 1), [3]. This water is transported through pipelines to the Effluent Treatment Plant (ETP) at Jaduguda for further treatment before discharged to the environment.

TABLE 1. MONITORING OF MINE WATER EFFLUENT FROM NARWAPAHAR

Location	No. of Samples	Parameters	pH	U (nat) $mg.m^{-3}$	^{226}Ra $Bq.m^{-3}$
Mine Water Effluent (Narwapahar)	24	Maximum	8.0	373	1245
		Minimum	7.3	14	133
		Mean	7.9	217	469
Discharge Limits	**In Inland Water**		**5.5 - 9.0**	**180**	**900**

Gaseous release

Exhaust air from Jaduguda, Bhatin, Narwapahar and Turamdih mines were monitored for their absolute radon concentrations. All radon releases were within the limits authorized by AERB for the respective mines. The measured values are given in Table 2 below [3].

TABLE 2. MONITORING OF GASEOUS RELEASE THROUGH MINE EXHAUST

Mine	Locations	No. of Measurements	Rn^{222} Conc. ($kBq.m^{-3}$)	
			Range	Average
Jaduguda	Adit-2	20	3.07 - 5.66	4.22
	Adit-4	20	4.27 - 9.29	5.90
Overall (Jaduguda)		**40**	**3.07 - 9.29**	**5.06**
Bhatin	Adit-3	19	1.75 - 3.04	2.24
Narwapahar	Adit	78	0.98 - 3.85	2.31
Turamdih	Adit	50	1.05 - 2.65	1.56

ENVIRONMENTAL MONITORING

Environmental radiation

Environmental atmospheric Radon–222 concentrations and external gamma radiation levels were measured at selected locations along the Tailings Pond fence using low level radon detection system, Alpha-guard and environmental radiation dosimeter. Results are summarized below in Table 3, [3].

TABLE 3. EXTERNAL GAMMA RADIATION LEVELS

No.	Location	γ Radiation Level ($\mu Gy.h^{-1}$)			^{222}Rn Conc(abs) ($Bq.m^{-3}$)		
		No.	Range	Mean	No.	Range	Mean
1.	Near water tap Dungridih N, TP-I	2	0.18-0.25	0.21	2	10-26	18
2.	Bhatin crossing, TP-I	2	0.40-0.60	0.51	2	22-30	26
3.	Separation bund Between TP-I & II	1	0.08-0.18	0.13	1	-	22
4.	Near Western hill side Fence TP-III	3	0.10-0.24	0.16	3	10-16	13
5.	South side fence near Chatikucha TP-III	3	0.08-0.17	0.13	3	8-28	12
6.	Near Dungridih (S) fence, TP-III	4	0.14-0.45	0.27	4	8-25	16
7.	Near Construction office at TP-III	1	0.12-0.17	0.15	1	-	8
8.	Near eastern side bund, TP-I	1	0.18-0.25	0.22	1	-	42
9.	Near eastern side bund, TP-III	3	0.10-0.20	0.15	3	10-36	20
10.	TP-III South East hill side	1	0.11-0.16	0.13	1	-	6
11.	TP-I, Inside Pond	1	0.80-1.30	1.05	1	-	39
12.	TP-II, Inside Pond	1	0.90-1.00	0.95	1	-	63
13.	TP-II Soil covered area	2	0.13-0.24	0.20	1	-	24

CONCLUSION

With an aggressive nuclear power programme, uranium mining activities in India is slated for further growth with the proposed opening of new mines in different parts of the country. During its 40 years of operation, uranium mining activities in India have exhibited technological and scientific excellence with utmost concern towards the safety of the people and the environment. Environmental control measures adopted at all the units are very stringent following the guidelines of national and international regulatory bodies. The Uranium Corporation of India Ltd. has successfully obtained ISO certifications for excellent work practices (ISO 9001:2000), environmental management practices (ISO–14001) and occupational health and safety management system (IS–18001) followed at different operating units.

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PAST URANIUM MINING IN PORTUGAL: LEGACY, ENVIRONMENTAL REMEDIATION AND RADIOACTIVITY MONITORING

F. P. Carvalho
Nuclear Technology Institute (ITN), Department of Radiological Protection and Nuclear Safety, Sacavém, Portugal

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Abstract

Extraction of uranium ore in Portugal started in 1908 for radium production and it was discontinued in 2001 with closure of the last uranium mine and milling facilities. In the territory, 61 uranium mines were exploited but mining and milling facilities were not properly decommissioned. The majority of mines were of a small size and most of the ore was chemically processed at the Urgeiriça mine facilities for production of uranium oxide concentrate. The uranium mining and milling wastes amount to about 13 million tonnes and required action to prevent dispersion of containing radioactivity materials and to treat acid mine waters. Site remediation measures were approved by the Government. Environmental remediation works were started in 2006 in the site with the main milling tailings, Urgeiriça, to cover the milling tailings. Waste disposal and remediation plans are outlined already for other mine sites. This communication summarizes the experience of uranium mining in Portugal, the assessment of environmental contamination in areas of old mines and of mining residue effects on the health of populations living in the area. Regulatory efforts made and lessons from past experiences are outlined.

INTRODUCTION

During most of the last century, Portugal was actively exploiting radioactive ores and for some time ranked as a main uranium producer. Mining for radioactive ores started in 1908 and this activity went on without interruption for almost one century. It ceased in 2001 with closure of the uranium milling facilities at the Urgeiriça mine, near Viseu. In the beginning, this activity was directed towards the production of radium and later on to the production of uranium.

As this mining activity encompassed a large number of sites, in total several thousands of workers were hired for prospecting, mining and milling tasks. With closure of the last uranium mine, populations were afraid that the mining company could walk away leaving mining waste and old mining sites unsecured. As many of these sites are located close to small towns and with a potential for impact on the environment and public health, boroughs required remedial action. This was approved by the Government and a State owned company, formerly in charge of mining, was recently committed with environmental remediation works. These works were started already at Urgeiriça and the company has planned for remediation of other mine sites also.

As the price of uranium recently rose again, uranium mining industry may resume activity in Portugal as well as in other countries. Therefore, it is important to assess past mining practices and learn with that experience to avoid making the same mistakes in order to reduce environmental impact and cost of future activities.

HISTORY OF RADIUM AND URANIUM MINING IN PORTUGAL

One may consider 4 phases in the history of radioactive ore mining in Portugal. The first deposit of radioactive ore was discovered in the country in the year 1907, and marks the beginning of the first phase. The first mining company, the French Society «L' Urane, Urban, Feige et C.ie» set up its chemical facilities by 1908 in the village of Barracão, near Guarda. During 5 years this company extracted radioactive ores from several mines, including Rosmaneira, Coitos, Sª das Fontes, Corredoura, in the Guarda region, producing pure uranium salts, and exported untreated ore and radioactive materials to France for radium production [1].

In 1912 this company became «Société Urane-Radium» owned by the Bank H. Burnay, Lisbon and in 1913 started radium production using the ores extracted from the mine of Urgeiriça, near Viseu. The former mines were abandoned. This company produced, in the Radium Salts Factory facilities at Barracão, pure radium salts and occasionally, alkaline uranates. In 1920 this Society changed the name to "Applications Scientifiques du Radium" (ASR) and, from 1925 to 1927, produced radium sulphate at Barracão and Urgeiriça. Other companies were formed in the late twenties that also produced radium as barium-radium sulphate. Altogether, from 1908 to 1926 these companies produced about 10 g (10 curies) of radium element.

Up to 1929 the main production was radium and uranium was seen as a by-product. In 1929 the company "Companhia Portuguesa do Rádio" (CPR) was created, a British – Portuguese consortium that explored several mining concessions until 1941. From 1929 up to 1940 some 40 grams of radium element were produced by this consortium and exported in the form of barium-radium sulphate to the UK. Production of radium was abandoned by 1944 and thereafter, the CPR focused on uranium production and pursued this activity until 1962. The CPR production was based mainly on the Urgeiriça mine ore, a large uranium deposit at European scale, where the radioactive ore extraction started in 1913 and was maintained until 1944 for radium production.

With the beginning of the "Atomic Age", since 1945 the extraction of radioactive ore was pursued for uranium production, while radium became a useless by product. This was the beginning of the second phase of the uranium history in Portugal. It should be pointed out that at that time the systematic prospecting of the country for uranium-radium ore had not been made yet and uranium production was carried out by a private company. The CPR based its production mainly in the ores extracted from two large mines, Urgeiriça and Bica, although it had maintained in exploitation 16 other mines until 1962 [2].

In 1949 the Portuguese Government set up a Commission for Atomic Energy that prepared the foundation of "Junta de Energia Nuclear" (JEN) in 1954 [3]. The foundation of JEN marks the beginning of the third phase in the uranium history in Portugal. This State owned institute performed the systematic prospecting of the territory for radioactive ores and built up the chemical plant for production of uranium oxide concentrates. JEN took over uranium production from CPR and continued it until 1975, year of the separation of mining activities from JEN institute.

With the creation of "Junta de Energia Nuclear", prospecting and mining were boosted. From 1955 to 1959 most of the national territory was prospected by aerial and carborne surveys. Uranium prospecting was made also in several territories in Africa.

Mining and chemical treatment of the ore were organized by JEN in central facilities located at Urgeiriça (Viseu) and Forte Velho (Guarda), both in the uraniferous province of Beira, in the Centre of Portugal (Figure 1).

The Chemical Treatment Plant was built up at Urgeiriça in 1951, and initiated treatment of uranium ore from Urgeiriça mine and from other small mines in 1952. It was able to process 50 000 tonnes of ore per year, producing U_3O_8 concentrates. Five facilities for static heap leaching were set up in other mines for uranium extraction from low grade ores not worth transportation to Urgeiriça facilities [2].

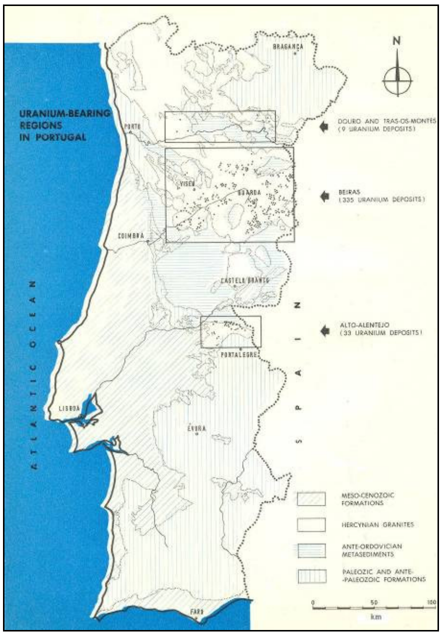

FIG. 1. Map of Junta de Energia Nuclear on the uranium regions of Portugal [2].

With the extinction of JEN in 1978, several activities carried by this institute were transferred to other institutes created in the same year. Mining would continue without interruption, thereafter carried out by the "Empresa Nacional do Urânio" (ENU) and years later transformed in ENU–SA [3]. This company maintained mining, chemical treatment of uranium ore, commercial operations and surveillance activities of previous mining sites, including those from CPR, until 2001. With closure of the last mine and discontinuation of uranium mining and milling activities, almost one century of this activity was completed. The extinction of ENU–SA marks the end of the third phase in the history of uranium mining in Portugal.

The ENU-SA assets and responsibility for closure of old mines was transferred to the State owned mine holding company "Empresa de Desenvolvimento Mineiro" (EDM), that set up a company fit for purpose, EX–MIN, entrusted for some time as the concessionaire for planning environmental rehabilitation of old mine sites. This marks the beginning of the fourth phase in uranium history. EX–MIN was reabsorbed by EDM in 2003 and the EDM holding took over responsibilities [4]. Currently, EDM initiated engineering works at Urgeiriça and in 2006 tendered for remediation works in several other mine sites. Environmental remediation of the old mine sites, of radioactive mines as well as several non radioactive mines, are foreseen to be completed by 2013.

GEOLOGY AND MINE AREAS

Uranium mineralization in Portugal appears at the province of Beiras in the granite massif and at the edge of this massif in areas of contact metamorphism of granites and, sometimes, disseminated in meta-sediments and schist with occurrence in Alto Alentejo. Most of the mineralization in Beira Province are of vein type in quartz gangue or associated with black minerals. All uranium mineralization have no thorium minerals. Uranium bearing minerals are the black minerals (pitchblende), gummite and coloured minerals such as autonite, torbernite and sabugalite [2, 5].

Since the beginning of the 20th century there was knowledge of some uranium-radiferous deposits. Based on geological and metallogenic information, Hercynian granites in northern and central Portugal, as well as contact aureoles between Ante-Ordoviciam metasediments and metamorphosing granites were considered favourable regions for uranium prospecting. However, at that time, prospecting was not systematic and knowledge of ore deposits was based on surface geology observations. Nevertheless, 99 deposits were recorded already and licensed by 1926, although many were never exploited [2].

Systematic prospecting of a large portion of Portugal was performed by the “Junta de Energia Nuclear” from 1954 to 1959. Prospecting was performed in phases starting with detailed aerial photo-geology studies, followed by campaigns with airborne sensitive Geiger Mullers, and by car borne scintillator detection systems. In more promising areas, finer prospecting was performed by local surveys followed by drilling and by electrical resistivity measurements to define the geological environments and the size of deposits. Trench and bore holes were used for estimation of the ore amounts available (Figure 2) [2, 5].

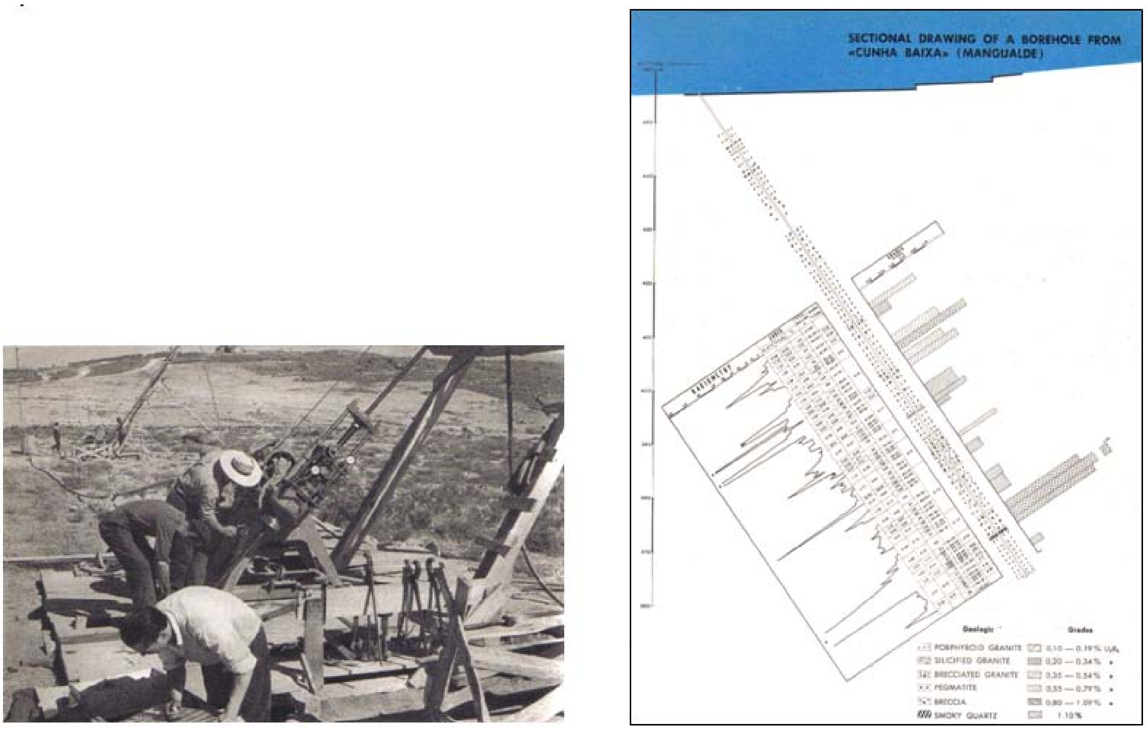

FIG. 2. Drilling to assess uranium deposit size and grade of the ore, in the fifties of last century [2].

From prospecting, nearly 400 uranium deposits were identified and 120 of them were studied in detail. Over the decades, 61 deposits were actually exploited and these were all in Beiras Province i.e. in the counties of Viseu, Guarda and Coimbra. Some promising schist impregnation deposits in the Alto Alentejo were never exploited.

URANIUM AND RADIUM PRODUCTION

Most radium was produced in the Radium Salts Factory build up in 1908 at Barracão, near Guarda. This facility ceased activities by 1926 but was not properly decommissioned and milling tailings with high radium and uranium concentrations remained there uncapped during decades, until removal by ENU to the Bica mine area [6].

The main facilities for uranium concentrate production were located in Urgeiriça (Figure 3). There has been chemical extraction also in Forte Velho, Cunha Baixa, Bica, Senhora das Fontes and Quinta do Bispo mines.

Rich ores from the small mines were sent to Urgeiriça for processing at the chemical plant. Low grade ores, not bearing extraction and transportation costs, were processed at the mine using an *in situ* extraction technique based on percolation of dilute sulphuric acid solutions injected in the rock. On surface by the mine, after appropriate milling, low grade ores were disposed of in piles and uranium dissolved by spraying or immersion in dilute sulphuric acid solutions (static heap leaching). The acid solutions (liquors) were then collected and uranium extracted back from acid solutions with ion exchange organic solvents or ion permutation resins in the Chemical Plant at Urgeiriça or at one of the main mine sites.

FIG.3. Uranium static heap leaching and dynamic uranium ore leaching tank facilities at Urgeiriça.

During the period from 1945 to 2001, a total of 4370 tonnes of uranium oxide (U_3O_8) was produced. Probably an amount between 50 and 100 grams of radium was produced also, from 1908 till 1944 (Figure 4) [7].

Most of radium was exported to France and United Kingdom and uranium oxide was exported to countries, such as UK, France and USA, implementing nuclear power programmes [1, 2].

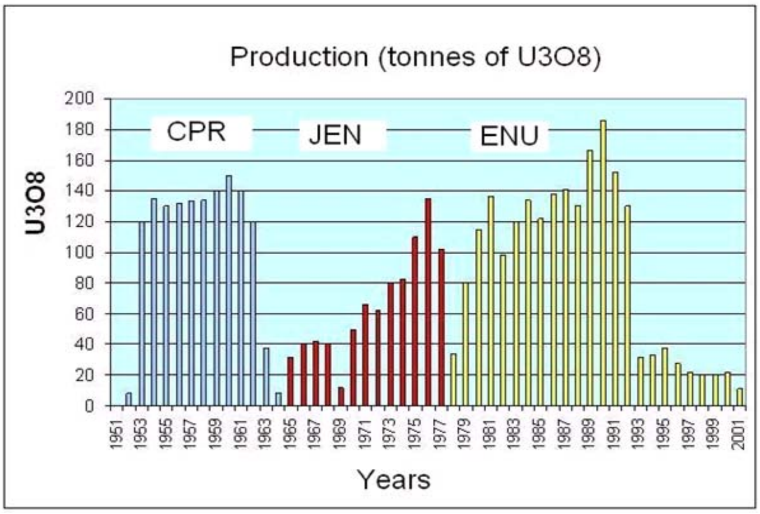

FIG. 4. Production of uranium concentrate.

LEGACY OF PAST URANIUM MINING AND MILLING ACTIVITIES

Over the years, 61 mine sites were concessioned to various companies for uranium ore mining. The ownership of the main concessions was transferred from one society to the next and by the end the «Empresa de Desenvolvimento Mineiro», the holding mining company received the ownership of all uranium mine concessions and also most of the old radium mines.

During the period of administration by JEN and ENU, many of the sites, including sites explored by the former CPR, were maintained under institutional control and radiological surveillance. By the end of this industry, the EDM holding received for closing out concessions that were reasonably identified and delimited. To date there has been limited environmental impact from waste heaps associated with these mines.

By 2001, most of the sites contained waste rock heaps left on the surface, or open peat mines flooded by rain. Several mines where sulphuric acid was used for uranium *in situ* leaching have mine water treatment plants in operation. An account of the mining and milling waste was performed by the Geological Survey and some preliminary characterization regarding radioactivity content was performed by ITN/DPRSN [7, 8, 9, 10, 11, 12].

With Law Decree 198–A/2001 the government approved a programme for rehabilitation of abandoned and degraded mine sites. This programme includes uranium mines and also tin, coal and pyrite mines all over the country. A total of 180 sites had been identified and among these 30 former uranium-radium mines. A more detailed waste inventory and characterization was performed by the concessionaire for remediation EXMIN for preparation of engineering plans to clean and close out the former sites [13, 14, 15]. As needed, EX-MIN installed also new signs and warnings to prevent use of materials (sands, gravel, water, etc); rebuilt fences and modernized acid water treatment plants.

At the same time the government nominated a Commission to follow-up the concession for remediation work (CAC) performed by the Concessionaire EX-MIN reporting to the Ministry of Economy. This Commission acted during 3 years, providing an independent analysis and advice to remediation plans and defined criteria to ensure compliance with environmental regulations and radiological protection measures [4]. The methodology agreed was based on the limit of 1mSv/y of added radiation dose to members of the public resulting from the environmental exposure to mining and milling waste after remediation, in accordance with European Union Directive 96/29 EURATOM. The work of this Commission (CAC) ceased in 2004 and EX-MIN was extinct in the same year. Implementation of remediation plans was commissioned by the Government to EDM.

The waste management plan adopted for environmental remediation includes *in situ* containment and capping of mill tailings at Urgeirça. For mining waste dispersed in the small mines it was considered to use as disposal sites the open peat of Quinta do Bispo, Murtórios, Prado Velho e the Bica mine. Each one will receive the waste from the group of mines in the respective region and will be used as a disposal and storage site. At the Urgeiriça site, the underground mine was flooded already. Water rose to the water table level, and pH and radioactivity are monitored. The chemical treatment plant facilities are to be dismantled.

The remediation of the milling tailings stockpiled near Urgeiriça was initiated in the late spring of 2006 (Figure 5). The engineering works consist in the transfer of tailings and low grade ores from the various heaps into one main area of tailings, Barragem Velha. These tailings are in the phase of reshaping contours to reduce the height of tailings and capping the tailings with clay, geo textile membrane, gravel and soil.

Acid mine water treatment for pH neutralization and co–precipitation of radionuclides is maintained in several mines, namely at Urgeiriça, Cunha–Baixa, Quinta do Bispo and Bica.

The overall cost of the remediation of radioactive mines is estimated in 12M Euros and should be completed by 2012 [13].

FIG. 5. Capping the main milling tailings at Urgeiriça (2007).

ASSESSMENT OF ENVIRONMENTAL CONTAMINATION AND EFFECTS ON PUBLIC HEALTH

Due to high concern of populations living near old mines and regional health authorities, the Portuguese Parliament recommended in 2001 an environmental and public health risk assessment of uranium mining residues. This was performed by 3 public laboratories in collaboration. The investigation encompassed the assessment of environmental radioactive contamination, contamination by other metals associated with the ore, and effects of residues on health of local populations. This included investigation of internal contamination of humans and chromosome aberration induced by population exposure to ionizing radiation [16].

Results of this project (acronym "MinUrar") were published in 2 public reports delivered in July 2005 and February 2007 to the government [17, 18].

The overall project results can be summarized as follows:

- There is some increment of environmental radioactivity from uranium mining and milling waste in Canas de Senhorim/Urgeiriça, however dispersal of waste containing radioactivity is small in geographic scale due to waste control exercised by the mining company over the years; enhancement of radioactivity in a local stream watershed and of groundwater did occur and should be monitored;
- Over the years, exposure to external radiation, to dust re suspended from uncapped tailings, and to radon may have elevated radiation doses to members of the public in this area in comparison with reference areas;
- Enhancement of uranium daughters' body burden in areas of ore mining and milling were detected through the analyses of radionuclides in human hair; and
- The health condition of the population inhabiting most of the contaminated area is on average lower than that of reference groups and frequency of chromosomal aberrations suggests enhanced exposure to radiation. No other sources of contaminants or exposure to other health detrimental factors were identified.

The MinUrar project delivered recommendations to the government. These were the endorsement of environmental remediation of these mining areas, and continued radiological monitoring of these areas after the remediation work, to ensure radiological protection of the population (Figure 6).

FIG.6. Report on the effects of uranium mining residues on the environment and public health.

REGULATORY CONTROL AND ENVIRONMENTAL MONITORING

During the performance of remediation works the EDM company is implementing radiological protection measures for workers and radioactivity monitoring in surface air (radiation dose, radon and dust). As recommended by CAC commission, the company aims at achieving environmental remediation in conformity with EU radiation protection standards. However, supervising and control by a regulatory authority in radiation protection and nuclear safety matters is still missing concerning the remediation works under way and its final verification. Future custody of the sites is not decided yet.

As part of its scientific and technical mission, the Nuclear Technology Institute through the Department of Radiological Protection and Nuclear Safety is in charge of environmental radioactivity monitoring in the territory, including the old uranium mining areas. This monitoring had been done in the past and it was resumed in 2007 for the purpose of ensuring the radiological surveillance and protection of environment and populations in these areas. Radiological surveillance includes the measurement of radioactivity in water, agriculture products and soils in the main uranium mining areas.

MAIN LESSONS FROM THE PAST

As many other industrial activities, uranium mining and milling have an environmental impact. In the case of historic uranium mining in Portugal, most of the activities were carried out before environmental regulations and radiation protection standards had been developed or were developed at the same time. The analysis of this historic experience shows positive and negative aspects.

The surveillance of, and restricted access to mine sites turned out to be effective in reducing the exposure of population to ionizing radiation and in avoiding the dispersal of mining waste materials. There have been few cases of re-use of gravel and sand containing radioactivity taken from mining and milling waste heaps. This was positive.

On the negative side, release of acid drainage from milling facilities into water streams caused contamination of creeks in mining regions. Fortunately, as the solubility of several uranium series radionuclides in aqueous media is small, radioactivity did not dispersed far from the mining concessions [19].

Contaminated soils and contaminated waters did occur mainly in areas where sulphuric acid was used in underground mines for uranium *in situ* leaching. This acid, adding to the acid naturally formed from sulphide, turned out to be the impact most difficult to control. Migration of acid into aquifers and resurgence in wells followed by use of water in irrigation, caused contamination of top soil layer and plants and, thus, poses the risk of population exposure though food chain radionuclide transfer. Furthermore, years of operation of acid water treatment plants in various mines where sulphuric acid was injected have been very costly. This mining method is today seen as non environment-friendly and should be carefully reconsidered in future mining operations [20].

The current environmental remediation works of old uranium mine sites and of the legacy of uranium milling tailings are worth 12M Euros or more. Most environmental remediation costs can be reduced if appropriate planning is made beforehand.

Based on environmental impact and remediation cost factors, in future mining it seems advisable to implement activities with adequate planning for:

- control of solid waste;
- improved control and treatment of acid drainage;
- reconsidering the use of uranium leaching with sulphuric acid;
- monitor air and water quality and as well as food chain transfer of radionuclides;
- protecting public health with interim measures (*e.g.*, water barrier to prevent radon emanation from waste heaps).

In view of the current radiation protection standards, it seems advisable to perform a site study before the start of exploitation in order to know the naturally occurring radiation background and to foresee how waste management and environmental remediation should be handled during and after uranium exploitation.

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STAKEHOLDER INVOLVEMENT DURING THE DEVELOPMENT OF AREMEDIATION CONCEPT FOR THE LERMONTOV URANIUM MINING SITE IN THE CAUCASIAN WATER DISTRICT*

P. Schmidt[1], A. T. Jakubick[1], J.Hartsch[2]
[1]Wismut GmbH, Chemnitz, Deutschland
[2] G.E.O.S. Ingenieurgesellschaft mbH, Freiberg, Deutschland

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Abstract

Commissioned by the European Commission, Wismut GmbH in collaboration with partners developed during the period 2004/05 a remediation concept for the Lermontov uranium mining site in Russia. Remarkable for Lermontov is its location in a tremendous countryside, in the centre of the Caucasian Mineral Waters region, and adjacent to famous spas. Identification of the technical solutions for rehabilitation of the uranium mining liabilities was not easy but could be managed on the basis of the broad Wismut know-how. More challenging however was to include the different stakeholder interests in finding the best suitable remedial measures. The paper deals with the social aspects of remediation, with questions of perception of radiological liabilities in the Caucasian Mineral Water region and describes how the different interests of stakeholders have been taken into account.

INTRODUCTION

In December 2003, Wismut GmbH was commissioned by the European Commission to implement the TACIS project EUROPEAID/116483/C/S "Remediation concept for the uranium mines of the state enterprise 'Almaz' in Lermontov, Russia". Following two years of intense work undertaken by a WISMUT-led consortium comprising WISMUT GmbH, its subsidiary WISUTEC, as well as C&E Engineering GmbH Chemnitz, and G.E.O.S Freiberg Ingenieurgesellschaft mbH, The final report on the project was submitted in due time and prime quality to the contracting authority in Brussels and to the parties involved in Russia in December 2005 [1].

At the Lermontov site, uranium was mined from 1945 through 1990 from two pits located in the Beshtau and Byk massifs, respectively. At the Byk site, ISL and above-ground leach pads were also in operation for some time (Figure 1). Low radioactive waste rock was piled up in the order of almost 4 million m^3. Milling produced 12 million m^3 of residues contained in a tailings facility of 85 ha surface located near the Lermontov ore processing plant GMZ (Gydrometallurgicheskii Zavod). During the 1990s, a number of various remedial actions were undertaken (sectional placement of covers on waste rock piles and tailings). Partial rehabilitation was conducted in the processing plant GMZ, since then, the unit produces phosphorous fertilizers and the by-product Phosphogypsum is deposited on the tailings facility.

FIG.1. Location of mining sites at the Lermontov site.

Compared to WISMUT, radioactive liabilities generated at the Lermontov site are definitely smaller in size. What greatly adds to the specific feature of the Lermontov site is its unique location on the northern Caucasus upland, in a landscape of stunning beauty (Figure 2), in the heart of KavMinVody, the Caucasian Mineral Waters region, surrounded by famous health spas such as Pyatigorsk, Kislovodsk, Essentuki, and Mineralnye Vody (Figure 1).

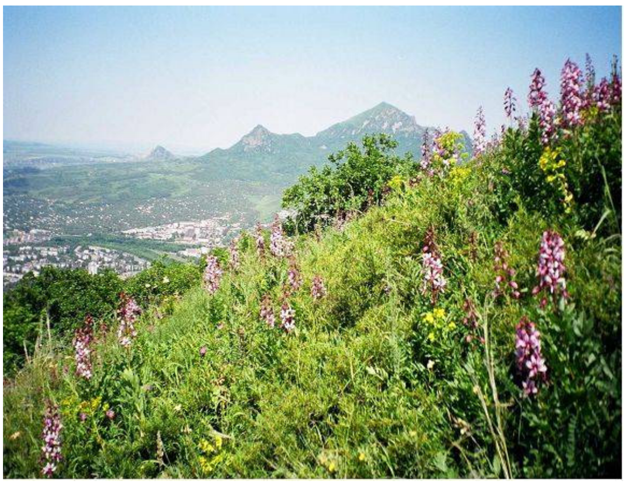

FIG.2. Scenery near the town of Lermontov with the Beshtau massif in the background.

This was the reason why the project was focussed on the sustained protection of the world's unique mineral water springs and the region's continued use for tourist and spa purposes.

The task assigned by the European Commission was divided into the usual steps to be followed in developing a remediation concept, namely:

- data collection and development of an object and environmental data base;
- development of a site model;
- environmental evaluation;
- feasibility study for the identified remediation options;
- optimization of remediation options; and

- conceptual remediation planning including estimate of costs.

In addition to the above items, training courses in dosimetric measurements and quality assurance as well as a workshop had to be conducted. The latter was intended to impart the experience gained during the development of the remediation concept and to highlight the pilot status which the European Commission had conferred to the Lermontov project. This included at an advanced state of the project to familiarize experts from other Russian and from Central Asian uranium mining sites with the approach to develop remediation solutions in accordance with European standards.

EXPOSURE SITUATION AND AWARENESS OF RADIOACTIVE LIABILITIES

Mining and processing of uranium ores amidst traditional spa and health resorts are difficult to imagine, but as is known such operations were also enforced by the Soviet occupying power in East Germany (Schlema, Ronneburg) and in the Czech Republic (Jachymov). Even more explosive is the subject of how to reconcile chemical leaching (both underground at the Byk mine and the heap leach operation near Byk) and the deposition over a wide area of radioactively and chemically contaminated ore processing residues (tailings) on the one hand and the use of mineral water springs in the immediate proximity of the mining sites on the other.

Therefore, during investigations on radiation exposure priority was also given to groundwater impairment. Contamination of low-lying aquifers feeding the mineral springs could not be established. Except for persons staying in the immediate vicinity of upcast air surface openings (exposure pathway inhalation of Radon/RZPr), exposures via the atmospheric pathway turned out to be insignificant. The dominating exposure pathway at the site was due to the use of mine waters and waste rock pile seepage collected in settling ponds near the mining sites. Fishing, irrigation of garden and field crops, even isolated cases of use for drinking water purposes were observed (Figure 3).

FIG.3. Fishing in a pond fed by mine water from the Byk site (adit #32).

Residents were unaware of the risks incurred or ignored them altogether. Local authorities simply dismissed the existence of this radiological exposure. Table 1 gives an overview of estimated radiological exposures which were established on the basis "Computation basis for the German mining industry" [2] and taking site-specific habits and consumption rates into account. The calculation approach in [2] leads to sufficiently conservative estimates. Bearing site-specific scenarios and habits in mind, the identified doses are far from being unrealistic.

TABLE 1. RESULTS OF CALCULATED EFFECTIVE DOSES FOR REFERENCE PERSONS P1 – P8

	Exposure scenario	Relevant exposure pathway	Effective dose [mSv/a] Child (2-7 years)	Adult
P1	Person having its permanent residence in the Bykogorka village, near waste pile 9, 250 h occupancy on waste pile 9	External radiation, Inhalation of Rn/decay products	0.58	0.53
P2	Person, staying 20 h at entrance or inside of adit 9	Inhalation of Rn/decay products	16.6	16.5
P3	Child playing 250 h/a on waste pile 9	External radiation, Inhalation of Rn/decay products direct ingestion	0.35	-
P4	Person with 6 months occupancy on datcha near waste pile 16 or 32; 250 h/a on waste pile (very conservative assumptions on dust)	External radiation, Inhalation of Rn/decay products, ingestion (direct, dust-laden foodstuffs)	2.3	1.7
P5	Remediation worker	External radiation, Inhalation of Rn/decay products, long-lived alpha emitters	-	0.9 - 10
P6	Person, drinking mine waters during datcha occupancy	Drinking water consumption	0.2 – **4.1***	0.2 – **4.8**
P7	Person consuming foodstuffs contaminated by mine waters (cattle watering, irrigation)	Ingestion of garden and field crops	0.2 – **7.9**	0.1 – **5.8**
P8	Person consuming fish caught in mine waters	Fish consumption	0.1 – **2.9**	0.1 – **1.9**

* Bold print indicates doses established using maximum radioactivity concentrations which in part were significantly above the guidance value of 1 mSv/a. Values in excess of this guidance value may indicate a need to consider remedial measures.

Presenting these findings to the local population, local bodies, and organizations was made difficult for the experts of the TACIS project on the ground who often encountered an atmosphere marked by a spirit of secrecy and cover-up.

TAKING STAKEHOLDER INTERESTS INTO ACCOUNT

Identifying and optimizing the purely technical solutions for the rehabilitation of the Lermontov sites (cover placement on waste rock piles and tailings, decommissioning of mines, controlled discharge and treatment of mine waters, etc.) were challenging tasks, not least because of the overriding importance to exclude any contamination spread via the aquatic pathway. On the basis of the know-how gained during rehabilitation operations conducted in the East German federal states of Thuringia and Saxony, Wismut GmbH and their partners in the consortium were able to develop and optimize such technical solutions.

As a matter of fact, these issues were not nearly as complicated as bringing into line the conflicting interests of the parties concerned by the remediation project (known as stakeholders). This stakeholder involvement evolved around three essentials to be taken into consideration:

Uncontrolled mine flooding versus utilization of radon-laden mine waters

The former owner of the mines had the intention to have the pits flooded and to then proceed to plugging and sealing of all surface openings. Such remediation measure would have been unsuited to preclude uncontrolled mine water discharges in the mid-term and the inundation of the former in situ leach field at the Byk site. A great deal of convincing had to be done by the German consortium to get the former owner headquartered in Moscow to adopt the concept of leaving adits open, purposefully discharging mine waters, and conducting subsequent water treatment.

Flooding and the subsequent plugging and sealing of the Beshtau mine would not only have entailed adverse ecological consequences, but also put an end to the availability of radon-laden waters. In an analogous operation to that at Bad Schlema or Bad Brambach, radon-laden waters from the Beshtau pit are pumped through a pipeline conveying the waters over a distance of 5 km to the town of Pyatigorsk where they are much in demand for curative purposes. It is largely due to this radon spring that the town owes its reputation as a health resort. The task in this context was to explain to the spa and health resort administration that the continued supply of radon-laden waters (including the urgent renovation of the pipeline) would require adequate financial contributions to the project. Operations models had to be demonstrated, since so far contributions were provided by the former mine's operator, i.e. the "State".

Production of fertilizers versus placement of a final cover on the tailings facility

According to the terms of a decree of the Russian president, chemical industries are banned from operation within ecologically sensible zones and therefore are not supposed to be present within the Caucasian Mineral Waters region. GMZ Lermontov, after all, has a licence to produce fertilisers which makes them by far the biggest employer in the region. The licence is bound to the disposal on the tailings facility of the by-product Phosphogypsum from fertiliser manufacture. This disposal should at the same time serve final covering purposes, i.e. the long term remediation of tailings (Figure 4).

Admittedly, such constellation could not be included into an EU-funded concept for the remediation of uranium mining liabilities. As the concept had to meet the requirements of a pilot solution for Russia it was to be measured against international standards to provide long term groundwater protection. Immediate placement of a cover on the tailings facility in line with European standards would, in turn, have deprived GMZ of the possibility to continue dispose of Phosphogypsum on the TMA. This would have meant the end of fertiliser manufacture and the biggest employer of the region would have been doomed to close down.

As a compromise solution, agreement was reached among all participants to contour the Phosphogypsum to serve as an interim cover (as a matter of fact, a gypsum layer of about 1m thickness would be suitable for this job) and to devise a sound concept for the final covering of the tailings facility in Lermontov prior to the expiration in 2008 of the licence to produce fertilisers. This will include a comprehensive investigation of the hydrological, geological, and geochemical conditions in the surroundings of the facility and of the underlying geological structures.

FIG.4. Covering of the tailings facility GMZ Lermontov using Phosphogypsum.

Modern water treatment versus use of water from mine water settling basins

Application of the indispensable solutions developed by WISUTEC to ensure the controlled discharge of contaminated waters and for passive water treatment schemes will prevent the continued use of mine waters from settling basins for garden plot irrigation and livestock watering. Notwithstanding the fact that using these waters will lead to intolerable radiological exposures, this was something that local representatives found difficult to accept (Table 1).

Henceforth, the submitted remediation concept and its implementation will make it compulsory for the local government and as well as the administration of Lermontov and Pyatigorsk to look for alternative solutions to provide water for the above purposes. The German consortium has identified a number of options to this end.

SUMMARY OF THE REMEDIATION CONCEPT'S BASIC ESSENTIALS

The remediation concept developed by the WISMUT GmbH-led German consortium comprises the following elements:

Beshtau mine:

- Strengthening of waste rock pile covers, stabilization of surface fractures;
- Plugging and sealing of shafts and adits;
- Repair of the pipe conveying the radon-laden water from within the mine up to portal #16;
- Controlled discharge of mine waters via portal #16;
- Construction of a passive water treatment unit to treat discharged mine waters; and
- Deconstruction of pond at adit #32; provision of alternative water for garden plot irrigation.

Byk mine:

- Strengthening of waste rock pile covers;
- Plugging and sealing of shafts and adits;
- Controlled discharge of mine waters via portal # 9;
- Construction of a passive water treatment unit to treat discharged mine waters; and
- Collection and treatment of seepage from the former heap leach pile #11.

Former GMZ Lermontov processing plant:

- Demolition of remaining contaminated buildings and facilities (remaining work);
- Area remediation; and
- Disposal on tailings facility of contaminated materials generated.

Tailings facility of GMZ Lermontov

- Postponement of closeout of radioactive residues until expiration of licence for disposal of residues from phosphorous fertiliser manufacture;
- Utilization of phosphogypsum as interim cover;
- Further investigation of hydrological and hydrochemical site conditions with the objective of developing an optimized final tailings cover; and
- Eventual tailings closeout by means of final cover.

CONCLUSIONS AND FUTURE PROSPECTS

Finding solutions capable of consensus-building while taking constraints into account which were not only site-specific but to some extent strongly marked by socio-economics: that was the real challenge in developing a remediation concept for the Lermontov uranium mining site. In doing so, all parties had to accept compromise that could only be found in overcoming traditional mind-sets. Frank discussion of significant radiological exposures and the common quest for solutions involving the parties directly concerned genuinely meant breaking new grounds in the true sense of the word.

Regular discussions of interim project status involving the parties concerned, authorities, former proprietors, operators, and potential users helped the WISMUT-led German consortium to press ahead with this process. Substantial progress was achieved by exemplifying rehabilitation operations and preparations for future use conducted at former Wismut uranium mining sites in Saxony and Thuringia. What's more, the same also held true for a workshop conducted in Chemnitz in the autumn of 2005 and attended by representatives from Lermontov, from other uranium mining districts in Russia, as well as from four Central Asian countries. On this occasion was also highlighted the potential waiting to be tapped by the former Lermontov mining site to fully integrate an emerging tourist and health resort region.

In August 2005, WISMUT/G.E.O.S. were able to present remediation options optimized with due regard to stakeholder interests to the local government of the KavMinVody region in Essentuki (on account of the region's unique mineral springs and health resorts, KavMinVody, by decree of the President of the Russian Federation, enjoys a special status and has self-administration (in the sense of local government)). The proposed remediation solutions were approved in the presence of representatives of institutions and authorities involved. Building on that outcome, conceptual planning and cost estimates for the remediation were performed. Costs for the remediation were put at EURO17 million and the implementation period at 4 years.

In the final report, WISMUT has suggested to the contracting authority that the European Commission support the remediation of uranium mining legacies at the Lermontov site on the basis of the submitted concept by adopting a follow-up project to provide technical and financial assistance as well as guidance and quality assurance. In the meantime, the Russian government has taken the necessary steps and submitted the application documents so that in case of a positive response by the European Commission remediation could start in 2008. Funding is to be provided by the Russian government and by grants from the TACIS Program of the European Union.

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REMEDIATION OF THE ZIROVSKI VRH URANIUM MINE

F. Avbersek, I. Gantar, Z.Logar
Rudnik Zirovski vrh, Todraz, Slovenia

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Abstract

The Uranium Mine Zirovski Vrh (RUZV) provided 630 000 tons of ore having an average grade of 850 gU_3O_8 /tons from which 452 tons of U_3O_8 were produced during the short life time of the mine from 1982 to 1990. In spite of the fact that the company paid considerable attention to protection of the environment, considerable remediation of the mine waste and of the site was required after the abrupt closure of the mine.

All adits and shafts into the underground mine were thoroughly sealed. The mine is situated in the hill of Zirovski Vrh above the level of the Brebovscica River that discharges the valley. Thus the mine water can leave the underground space at the lowest level of the mine by natural outflow. Although a small water treatment plant exits at the river discharge point, no treatment of the mine water is necessary. Water drainage boreholes shortcutting the underground water flow from the hanging wall above the ore deposit and covered concrete channels were constructed to prevent the contamination due to possible future disturbances in the mine. Extensive underground mine openings were backfilled with a mixture of concrete grout and waste rock to prevent damage and preserve the impermeability of the mine structures toward surface water. Where possible the backfill was trucked directly to the mine stopes, other parts of the mine were backfilled from the surface by means of injections through boreholes.

The mill and associated structures were demolished, the debris trucked to the central mine waste site and the site decontaminated. The equipment, which could be decontaminated, was sold as scrap metal; the contaminated metallic waste, other useless metal, synthetic materials, etc. were safely deposited in waste rock piles.

Temporary mine waste piles were relocated to the central mine waste pile at Jazbec. The mine waste pile was reshaped to minimize the slopes for better long term stability. A multi layer cover including a water tight layer was constructed on the surface of the pile to minimize leaching of the contaminants from the waste rock pile to a degree that was feasible. An existing seepage water culvert under the pile was rebuilt and water monitoring point established. The surface dewatering channels and auxiliary structures (fences, roads, etc.) will be finished in the year 2008.

The remediation work started at the mill tailings site Borst in May 2007. The landslide under the tailings was previously stabilized by construction of a dewatering tunnel and drainage wells from the tunnel. A rock toe to stabilize the north face slope was constructed. This enabled the start of construction of the central and lateral drainage curtains for dewatering of the tailings and to reshape the tailings surface. A multi layer cover is planned to minimize the percolation of rainwater into the tailings. All works are planned to be completed in 2010. A monitoring system controlling the soil mechanical, chemical and radiological factors will be installed for long term stewardship of the sites.

INTRODUCTION AND BACKGROUND

Zirovski Vrh Uranium Mine (RUZV) (Figure 1) is situated 45 km west from Ljubljana, capital city of the Republic Slovenia. Uranium mineralization was found in 1960, the ore exploitation started in 1982 and the yellow cake production in 1984. The production ceased unplanned by oral notification of the Ministry for Energy to the mine management in 1990. The Decree and corresponding Act followed latter in 1990 and 1992 [1] [2]. Only 610 000 tons of sandstone ore with 0.7 kg U/t were processed and 452 t of yellow cake were produced. A total of 3 307 000 t of rock material was excavated (630 000t of high grade ore, 206 000 ton of low grade ore and 2 468 000 t of mine waste).

When the Government decided to stop the production there were no plans and no funds allocated for the mine remediation purposes. In this way the company started to prepare remediation plans, technical documentation (including safety reports), and investment documentation and to obtain necessary construction permits and to resolve the social problems of the workers. The solution of all these problems had taken a lot of time before the main remediation works started in an adequate way in the field in 2002. During the whole period the company has been assuring safety and control over the mine underground and surface sites, with the main emphasis on the mill tailings site.

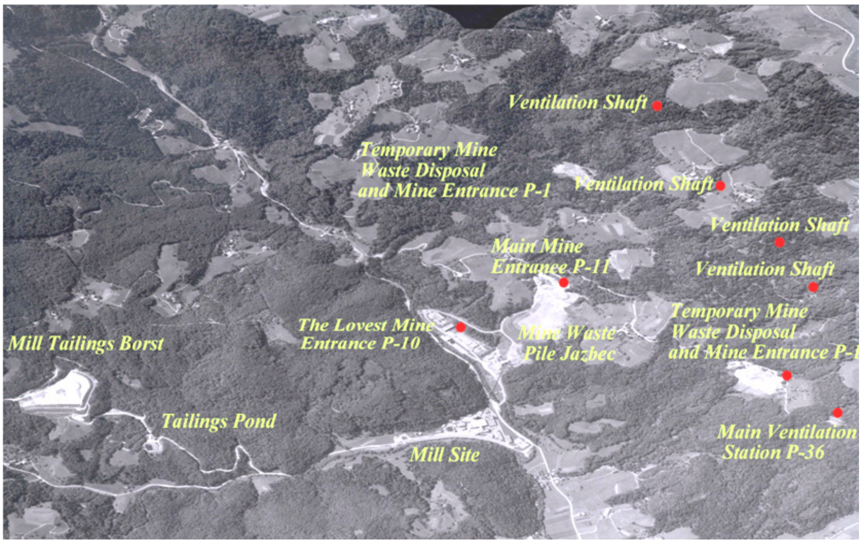

FIG.1. Mine surface sites in 1990.

The events of note were:

- Remediation of the mill site including safe removal of the process chemicals on the base of operating license (1991–2000);
- The mill tailings site landslide was stabilized with dewatering wells and T shaped dewatering tunnel (1994–1996);
- Decommission and transfer of the mine auxiliary buildings to the Ministry of Defense (1996);
- Remediation of the underground mine was completed in period 2002–2006;
- Remediation by relocation of small temporary mine waste piles was completed in 2006;
- The central mine waste pile remediation started in the second half of 2005; and
- The mill tailings site remediation started in 2007.

Due to the introduction of additional safety improvements and the delays in completion of the planed remediation works, a few investment programs has been required up to now [3–7]. Total remediation costs are estimated to be 86.3 Mio EUR. Table 1 shows the total amount of money required for the site remediation split in different time periods. Table 2 shows the funding requirements for completion of the remediation split in different categories. Figure 2 presents the remediation schedule until completion of the construction activities. Regular stewardship of the site will continue after that time for all long term remediated sites.

TABLE 1. TOTAL URANIUM PRODUCTION SITE REMEDIATION COSTS [8]

Period	Funds (Million EUR)
2006 - 2010	28,8
1990 - 2005	57,7
1990 – 2010 Total	86,3

TABLE 2. SUMMARY OF THE CLOSEOUT COSTS NOVELTY NO. 2 TO THE PROGRAM IN 000 EUR [7]

Type of Cost	Total Needed 2006-2010	2006	2007	2008	2009	2010
Ore Winning Plant	**1.737**	1.737	0	0	0	0
Uranium Concentrate Production Plant	**0**	0	0	0	0	0
Mine Waste Piles	**9.513**	1.724	3.299	4.490	0	0
Mill Tailings Borst	**12.317**	636	2.301	3.767	4.114	1.498
Subtotal	**23.567**	**4.098**	**5.599**	**8.257**	**4.114**	**1.498**
Conditions Assurance	**2.403**	755	576	400	329	343
Monitoring and management	**2.166**	339	346	426	440	615
Damage Claims	**513**	154	142	75	75	67
Subtotal	**5.082**	**1.248**	**1.063**	**901**	**845**	**1.025**
Total	**28.650**	**5.346**	**6.663**	**9.158**	**4.959**	**2.523**

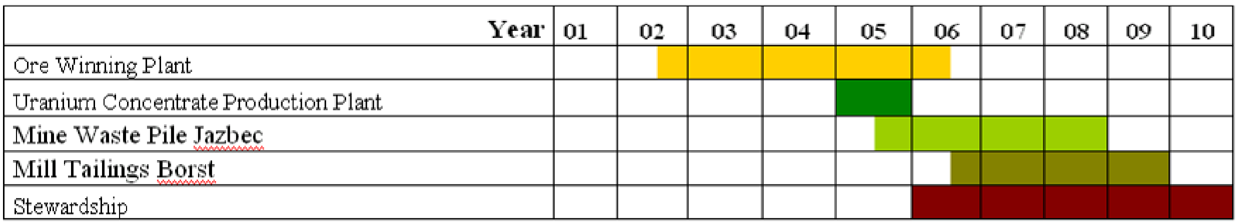

FIG.2. Time schedule to finalize remediation works [7, 8].

REMEDIATION PROJECTS IN VARIOUS COUNTRIES

A similar project of much greater scale than at RUZV has been going on at Mecsek Uranium Mine near the town of Pecs, Hungary. Following the funding problems and idle time in the field remediation at RUZV they scheduled the cessation of the production in a technical manner. Technical cooperation between these two mines has been going on since 1990.

SPECIFIC REMEDIAL SOLUTIONS

Mining/ISL

The underground mine extends 2800 m in a Northwest-Southeast direction, 150m Northeast-Southwest and in height up to 180 m. About 60 km of underground mine openings were mostly built having a cross section to allow trackless mechanization for production and transport. The mine was divided in 4 horizons into 14 blocks of 200 m width. Uranium ore was mined by room-and-pilar method. The deposit occurs in Groeden Sandstone of Permian age (Figure 3).

After cessation of the ore production the company took care to secure the mine workings and underground sites of the infrastructure (ventilation, electrical power distribution, water treatment, passage of the tunnels, etc.). RZV miners performed minor remediation activities (remediation of mine change rooms and workshops for other’s use, etc.). The main work was to assure safety condition for the contracted workers. During this period the mine closeout plans and drawings were prepared. It was decided that the mine water would drain through the lowest adit P-10 without any treatment, due to low chemical and radiological contamination (uranium concentration below 300 $\mu gU_3O_8/l$; water flow 40 – 60 m^3/h).

The contractors had started permanent remediation in 2002, when the funds were secured; the work was completed in 2006.

The following works had been done until conclusion:

- Building of channels, dams and catchers (sand traps) for controlled drainage of the mine water through the mine tunnels;
- Drilling of drainage boreholes in the pit to drain up upper horizons with open ore stopes and to prevent contamination of the mine water in the outlet from the mine and to keep contaminants concentrations in prescribed limits issued by the competent authorities [6];
- Filling of the shafts and adits connected to the surface to a depth that prevents influence on the surface by cracking roof process;
- Remediation of adits and stopes, sunk by the mine water, by partial filling with adsorption rock to prevent flowing water contamination from the ore surfaces of open stopes;
- Permanent deposit of the ore, contaminated materials from the dismantling of technological equipment and geological samples;
- Demolishing of the mine surface sites;
- Filling of the abandoned mine places to prevent influence onto water impervious Jazbec nape and inflow of the surface water to the mine; and
- A new building was constructed with the mine water flow measurement instrument and sampling point.

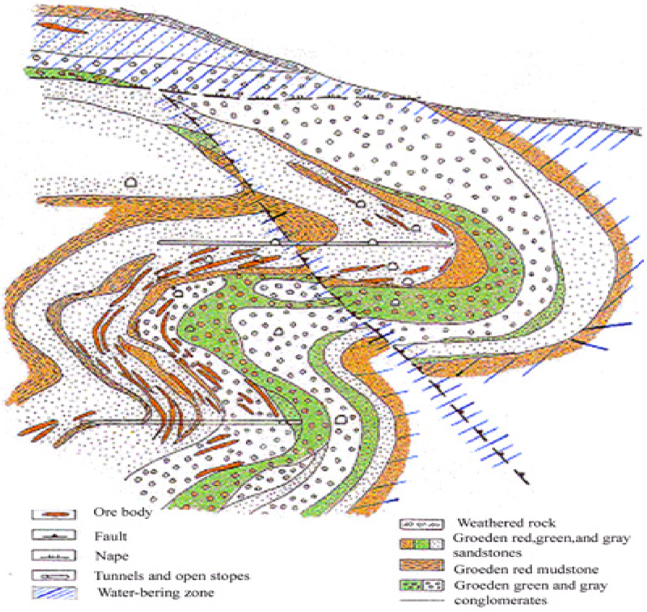

FIG. 3. Geological profile of the Zirovski Vrh Uranium Mine [14].

To perform the required backfill of the mine openings, two methods were utilized. First was transportation of crushed mine waste by mine trucks and backfill. The second utilized method was cement paste of crushed waste injection into unsafe and inaccessible stopes through the boreholes (diameter from 0.3 to 0.6 m) from the surface (Figure 4). Table 3 shows quantities of the materials backfilled or deposited in the mine during the remediation.

TABLE 3. MATERIALS USED FOR THE MINE BACKFILL [15]

Location of the Backfill	Type of the Material	Quantity (t)
Blind Shafts in the Mine	Concrete of the mine waste	21 763
Mine Tunnels Backfill	Concrete of the mine waste	23 211
Backfill of the Ventilation Shafts to the surface	Concrete of the mine waste	11 343
Backfill of the Entrance Tunnels	Concrete of the mine waste	8 613
	Concrete of inert materials	39 250
Geochemical Barriers	Weathered Karnian Clastites	10 026
Containers with Contaminated Materials Deposition	Geological samples, etalons	31
Backfill of Opened Mine Rooms through Boreholes from the Surface	Concrete of the mine waste	34 464
Ore 1991 - 2004	Ore 468 gU_3O_8 /t	18 807
Total		**167 508**

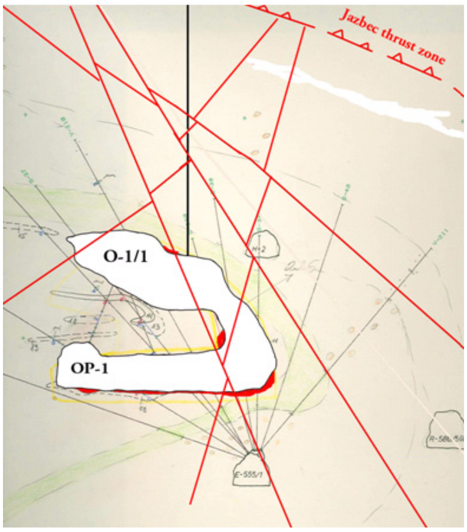

FIG.4. Geological profile P-34 with open room and vertical injection borehole (black) and faults (red) [14].

FIG.5. Mine stope roof demolition process (By Begus).

Numerous different, mainly temporary and smaller mine waste piles had been developed during geological exploration, the mine construction and the ore exploitation periods. The contractor relocated contaminated materials to the central mine waste pile Jazbec and remediated these sites. In total more than 470 000 tonnes of material (mine waste and contaminated soils) has been relocated in 15 years. This figure does not include the wastes from the mill site remediation [11].

Mine waste pile Jazbec

The waste pile was constructed with the mine waste backfill of the Jazbec Brook ravine. The Jazbec Brook was captured before that and led into polyethylene pipes and further down into a concrete culvert (329 m long) that dewaters two smaller torrents. The Jazbec valley is cut by the Hotavlje fault, with some wet moors on the surface (Carbonian schist's with low water conductivity at the upper part of the pile). At the bottom (lower part of the pile) are dark grey limestone outcrops showing characteristic Karstic properties (Carnian limestone's and Norian dolomites). That is important from the seepage water point of view and spreading of contamination by groundwater. The channels are parallel with Hotavlje fault and have common Karstic spring water 2.5 km down which is contaminated.

From 1983 to 2003 1,716 000 tonnes of the mine waste was deposited, 197 000 tonnes of poor ore and 48 000 tonnes of red sandstone. The area of the waste pile is 6.7 ha and has not been covered yet. The slope of the waste pile is 1:2 with 3 m wide berms placed at each 12 m height. At present the highest point is 510 m a.s.l. The culvert discharge is at 430 m a.s.l., average yearly waterflow is 30 m^3/h.

The contractor started with the remediation works in August 2005. The construction plan includes the following works:

- Diversion of the watershed brook (the Brdarcek torrent) disburdening flood load of the Jazbec Brook;
- Regulation of the watershed part of the Jazbec Brook and surface diversion of it to secure the flood waters draining;
- Reshaping the waste pile to obtain the slopes lower than an angle of 20^0. The berms will be constructed every 10 m;
- Engineered cover construction, thickness 1.95 m with the properties of the local material is shown in the Tables 2 and 3 [11];
- Construction of the dewatering channels to drain rainfall waters;
- Upper part of the Jazbec culvert will be filled with cobles;
- Repair of the Jazbec culvert, a part that remains in function;
- Monitoring wells and surface water monitoring sites construction, set up of geodetic measurements points;
- Fence installation to restrict access of the public; and
- Plans for long term stewardship of the site.

The lowest point of the waste pile will be at 429 m; the highest point will be 509 m. At this point stone monument will be constructed.

TABLE 4. COVER DESIGN OF THE MINE WASTE PILE JAZBEC

	Layer name	Material	Kind of material	Planned water conductivity
	Vegetation			
0,25 m	Vegetation layer	Humus, soil	Humus soil	1 x 10^{-6} m/s
0,50 m	Transitive layer	Karnian sandstone	Rubble 0/63mm Local rocks »Jaka«	1 x 10^{-7} m/s
0,80 m	Protection layer	Karnian sandstone	Rubble 0/63mm Lokal rocks »Jaka«	5 x 10^{-8} m/s
0,40 m	Seal layer	Karnian mudstones	Fine, clayesh sand and natural rubble »Jaka«	5 x 10^{-9} m/s

FIG.6. The mine waste pile remediation development (October 2005 and 2007).

Milling, processing and water treatment

RZV performed chemical liquidation of the process inventory in the period 1991–1993, partial decontamination of the mill site 1994–1997. Demolition and relocation of the ruins and contaminated soils to the central mine waste pile Jazbec was done in 1998–2000. The officially nominated commission approved the site for free use and authorized authorities issued the decree in December 2000 [10].

The mill site ownership was transferred to the community of Gorenja Vas–Poljane in 2003 on the basis of the agreement among the Ministry of Environment and Spatial Planning, RZV and the Community. Only auxiliary (boiler room, change rooms), laboratory and office buildings remained in RZV's use. As agreed, the site will become an industrial zone in the future.

Mill tailings

From the beginning of the operation till the end of uranium production at Zirovski Vrh Mine, 610 000 tonnes of mill tailings had been generated and deposited on the tailings pile Borst. To allow access to the tailings ground regularly, roads were constructed at every 5m of elevation using 73 000 m^3 of mine waste rock. The tailings pile has an area of 4.2 ha. The site is about 2 km away from former mill. The tailings body is cut by landslide (3/5). The tailings were sited in the slope of the hill to minimize radon exhalation impact on population in the Brebovscica Brook valley.

Geological circumstances

The geological foundation of the tailings site consist of Upper Triassic (Carnian) sediments, yellow, red and gray fine grained sandstones, altering with aleuritic layers with tuff and tuffaceous inclusions. Tuff and tuffaceous materials contain higher concentrations of montmorilonite and illite that swell in presence of water. Carnian clastites were strongly affected during the Alp orogeneze due to proximity to the overthrust. The whole area is very tectonically affected due to bad geomechanical properties of the clastic rocks. A large number of sub-vertical faults disrupt the geological base. At the joints and faults the cracks aquifer system under pressure was formed. This groundwater comes from porous Cordevol dolomites and supply water into the body of the tailings through the faults. Some springs were captured before the tailings construction started.

After heavy rainfall in November 1990 a crack with 20–30 cm of vertical movement appeared in the road on top of the tailings due to land sliding. The extent and depth of the sliding area have been established by extensive geological and hydro geological explorations.

The landslide occurred on the contact of the Carnian clastites and tuffaceous rocks, average thickness is 50 m.

Tailings moved by landslide	328 579 m^3
Masses of ground moved by landslide	2 593,175 m^3
Total volume of the landslide	2 921,154 m^3

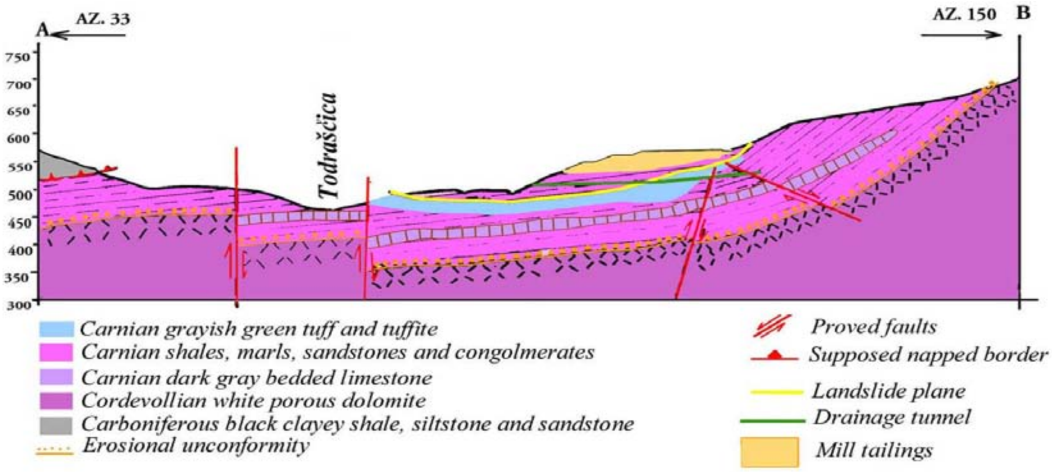

FIG.7. Geological profile of the mill tailings site (By Gantar).

Landslide stabilization

The main effect on the movement of the landslide was achieved by the construction of the drainage tunnel in 1995. The tunnel starts in the sliding face crossing the main sliding plane at about 214 m from the entrance of the tunnel. At the upper end of the tunnel two drainage tunnel wings were excavated. Vertical wells (24) drain the water into the wings. The water flow from the drainage tunnel is from 0.5 l/s to 21.5 l/s, with yearly average 2.2 l/s [13].

FIG.8. Excavation of the central drainage at the mill tailings (redline shows the course) (Photo Likar).

FIG.9. Excavation of the backside water drainage and fill with water conductivity materials to protect the mill tailing against the subsurface water inflow (Photo Likar).

Proposed solution

It was demonstrated during implementation of the test covers in 2002 and 2003 that tailing's tixotrophy, groundwater and stability are problematical. The Director of RZV nominated a commission of professionals (civil construction, landslide and groundwater specialists) to find optimal technical measures as a solution of the above mentioned geotechnical problems. The commission proposed the following measures:

- Implementation of the safety – supporting dam – rock scarp at the heel of the northern and western slope. In the area of the western slope the existing road can be used as foundation;
- Implementation of the central drainage curtain in the tailings in the area of the wettest zone that is approximately in the centerline of an old brook bed to lower the groundwater in the tailings. Monitoring of the effects;
- Implementation of the drainage curtain wall in the hinterland of the tailings to prevent hinterland water inflow. Monitoring of the effects;
- Reinforcement of the material in the tailings in the area of the northern slopes and supplement the northern slopes with stone material with shaping of new surface to slope 15 ^{0}. Monitoring of the effects;
- Sanation of the existing drainage system in the tunnel (wells). Arrangement of the contact among wells and surface of the terrain;
- Implementation of the watertight cover;
- Surface drainage of the area of the impact. Monitoring of the effects; and
- Implementation of additional drainage tunnels (if the landslide wouldn't be stabilized).

Technical measures that will have to be implemented are presented in the order they have to be followed. The last measure in the list doesn't mean the least important one, but this is a measure that will be implemented at the last stage [12].

The detailed design is takes into consideration the above mentioned measures and goals. It was decided to use clay with good hydraulic characteristics instead of local material (Jaka burrow). The cover design is given in Table 5.

TABLE 5. COVER DESIGN OF THE TAILINGS BORST

	Layer name	Material	Kind of material	Expected water conductivity
	Vegetation			
0,25 m	Vegetation layer	Humus, soil	Humus soil	1 x 10 $^{-5}$ m/s
0,50 m	Transition layer	Crushed Karnian sandstone	Rubble 0/63mm Local crushed rocks »Jaka«	1 x 10^{-7} m/s
0,80 m	Protective layer	Crushed Karnian sandstone	Rubble 0/80mm Local crushed rocks »Jaka«	5 x 10 $^{-8}$ m/s
0,50 m	Seal layer	Clay	Clay, clayish mud	5 x 10 $^{-10}$ m/s

Regulatory, socio-economic and stakeholder issues

The RUZV and the Government of the Republic Slovenia has presented satisfactory care for redundant workers and loss of economic power of the community due to the mine closeout. The workers received monetary compensations the community company's land and infrastructures for the industrial zone development. The state payments for damage caused to the community of Gorenja vas-Poljane are under negotiations.

Monitoring and surveillance

RZV will perform stewardship over the closed mine long term sites and will perform the mine water control in the interim period for the first five years after closeout (2010 to 2015).

Post-remedial utilization

Slovenian Radioactive Waste Agency (ARAO) will perform stewardship management after the transition period. There are no plans for an economical utilization of the long term sites like remediated mine waste piles. Considerations have been going on to utilize the mine waste area as a part of recreational and tourist area. All other company land has been transferred to public ownership or returned to its former owner. At the former mill site the industrial zone has been successfully introduced by different small entrepreneurs.

PROACTIVE REMEDIAL MEASURES IN OPERATING MINES

There are no active uranium production facilities in Slovenia. The authors are not familiar with any future plans in this sense.

OUTLOOK AND FUTURE CHALLENGES

The RUZV plans to perform stewardship of the remediated site during transition the period i.e. until 2015. On the basis of data obtained from overall monitoring the responsibility for stewardship will pass to ARAO.

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DECOMMISSIONED URANIUM MINES IN UZBEKISTAN – IMPACT ON ENVIRONMENT AND HEALTH

E.A. Danilova, A.A. Kist, A.V. Mukhina, R.I. Radyuk, G.A. Radyuk, U.S. Salikhbaev, A. Vasidov, A.A. Zhuravlev
Institute of Nuclear Physics, Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

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Abstract

Uzbekistan (as well as some other Central Asian Republics) was in the past and is in the present an important producer of uranium. After 1996 only ISL uranium mines remained operational. All conventional "hard rock" mines were decommissioned leaving behind sizable volumes of mine wastes and mill tailings and contaminated sites. For the preparation of the remediation of these legacy wastes and sites it is very important to first create a reliable data base on which the preparation of the remedial strategy could be based. The problem of the legacy sites is complicated by the fact that the former uranium mining sites are located in the mountainous part of the country and close to rivers that are used by the local population as a source of water. The situation is further complicated by the geo-morphology of the sites, which makes the mine wastes prone to be dislocated by mudflows.

To obtain a first appraisal of the radiological situation at the uranium mining legacy sites, the Uzbekistan Academy of Sciences went on investigating two sites: Yangiabad and Charkesar.

A great number of measurements of the gamma radiation, radon concentration and analysis of radionuclides content in various media on the sites were carried out. The effective radiation doses due to exposure to radon were also determined. The radionuclide content in the foodstuff produced on the sites and in the vicinity was analysed and the exposure via ingestion appraised.

The collected data and information provides important background information for prioritization of the remedial actions and for development of a more focused investigation program for the sites.

INTRODUCTION

Uzbekistan, along with Kazakhstan is a significant producer of uranium in Central Asia. However, similar to the other Central Asian countries, there is no conventional mining of uranium ores in Uzbekistan at the present. All former "hard rock" uranium mines have been decommissioned.

As a result of the past uranium production, considerable tailings storage sites and mine waste rocks piles were left behind that are both radioactive and contain toxic elements. In this conjunction it is necessary to note that the former conventional mines and consequently the mine waste dumps are located in the mountainous part of the country. These legacy sites were often located near rivers, which then became the recipients of the contaminated drainage from the closed out mines and mine waste dumps. In addition to the fact that these rivers are often used by the local population as their source of water, the potential hazard for the population and for the agricultural land in the vicinity is aggravated by the morphology and climatic conditions in this part of the country causing that mine waste dumps sometimes become mobilized in the form of mudflows, which then flow into the rivers. The described situation was the rationale for our investigations of the radioecology at these sites. Based on these investigations the risk associated with the legacy sites can be assessed and the strategy for remediation developed to protect the health of the local population.

It should be stated that the problem of the uranium mining and milling legacy is a very important issue in all Central Asian countries, which share many similarities in the history of the mining and processing, have comparable climatic, hydrographic conditions and morphology as well as wide exchange of agricultural produce, etc.

Furthermore, it is of importance to note that some of the former uranium mines of Kyrgyzstan are located close to the borders of Uzbekistan. For example, one of the largest decommissioned uranium mines of Kyrgyzstan is only 8 km away from the Uzbek border and presents for the population in Uzbekistan more than 50 times higher risk than for the population in Kyrgyzstan. The situation near to the border of the country is visualized in Figure 1.

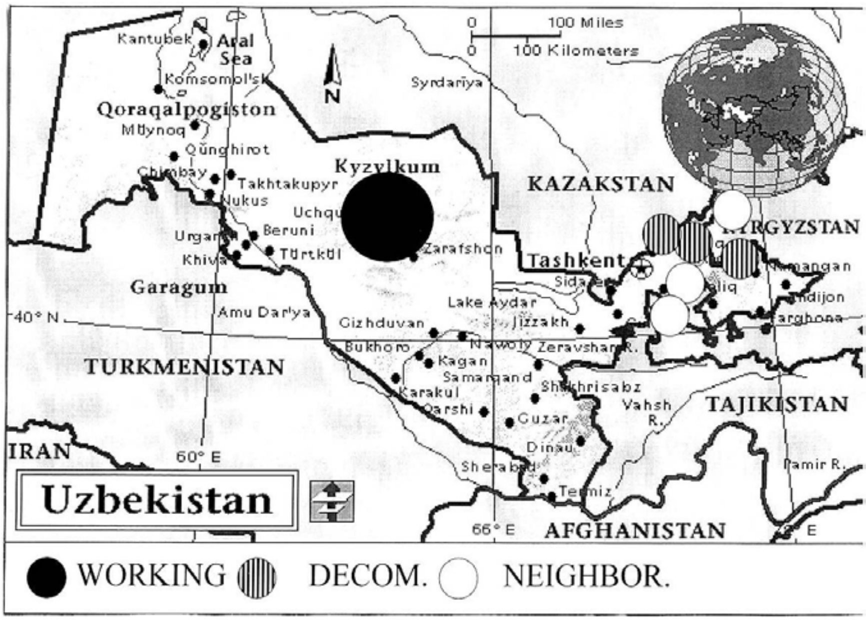

FIG.1. Uranium mines in Uzbekistan and close to the state border.

A number of survey campaigns were organized to carry out the environmental monitoring at the sites of former uranium mines with the objective to measure the gamma dose rates, indoor and outdoor concentration of radon (^{222}Rn) in the air, sample the water, soil and food. The surveys were carried out in Yangiabad (Tashkent district) and Charkesar (Namangan district in the Fergana valley).

The village of Yangiabad is situated 140 km from the capital of Uzbekistan, Tashkent. The extent of Yangiabad is approximately 77 hectares. In the village there is a medical “polyclinic”, municipal hospital, kindergarten, children's nursery, school, residential housing and other public buildings. The buildings in the city were built in the 1950s from materials imported to the site; only a few buildings were built using local materials (which was not necessarily taken from the mine site). The town borders on the legacy site where the radioactive mine waste has been deposited. The area of the legacy site is 50 km^2, which contains a total of ~500 thousand m^3 of radioactive mine wastes. The gamma radiation rate of the contaminated areas is from 0.60 to 2.0 μSv/h. All mine waste is outside of the town but close enough to inhabited areas, which makes the monitoring of the site and of the inhabited areas very important.

The village Charkesar is situated 20 km from the city of Pap, which is a regional centre of the Namangan district (Fergana valley). The city has schools, kindergarten, hospital and other public buildings. This village is very close to the decommissioned uranium mine.

The uranium deposit Charkesar has been mined by two mines – Charkesar–1 and Charkesar–2. Uranium was produced using both conventional mining and underground leaching to a depth of 280 m. The radioactive mine wastes are stored in dumps covered with uncontaminated soil. Parts of the cover were, however, damaged by rain erosion.

The volume of radioactive mine wastes at the site is estimated to amount to 480 thousand m^3 and contain a total amount of radioactivity of $3x10^{13}$ Bq. The mine waste is spread over an area of 20.6 hectares.

There are three large waste rock dumps on the site and one open pit mine. The site is protected from the city by a 1m high stone wall. The wall has been in several places destroyed, thus providing easy access to the mine site for both population and cattle. The exposure dose rate on the site is in a range of 3.0–4.5 μSv/h.

The mine water discharges from the underground mines at several places and is readily available for the inhabitants and livestock. The yield of the discharges is between 3–5 l/s. Upon surfacing, the mine water discharges create little creeks flowing toward the small stream separating the legacy site from the city. The mine water contains high concentrations of uranium, radium and radon.

Already all the described factors at the legacy site make the situation of Charkesar very unfavorable.

To more precisely assess the problem at the site further examinations of the mine waste dumps are needed, such as:

- Continuation of the radio-environmental monitoring;
- Estimation of the exposure doses to the critical groups of the population of Charkesar and implementation of health protection measures; and
- Collection of the data necessary for the development of a site remediation project.

For the present measurements on the site the following equipment was used:

- Radonometers for the active method (RA), passive method (PRM, SARAD-Scout, RAMON-01) and solid state nuclear track detectors, SSNTD, CR-39);
- Dosimeters for gamma rate measurements (Target, Polymaster);
- Gamma spectrometers with HPGe detectors;
- GPS and photo cameras; and
- Sampling equipment.

RADON

During the past years the radiation risk of radon-222 and its decay products has been widely discussed in the world. The sources of radon in the environment of the general public can be the soil, ores, water, mine wastes, mill tailings, building material, etc. The concentration of radon-222 usually correlates with the uranium content of these materials.

The degree of health risk for the members of the public does not depend solely on the effective exposure dose rate but also on the duration of exposure and age of the exposed person. The risk of development of a cancer mild due to radon exposure is decreasing with age and for smokers the risk increases approximately 10 times [1]. The International Commission on Radiation Protection (ICRP) specifies the permissible level of indoor radon concentration as 200 Bq/m^3. Concentrations higher than 400 Bq/m^3 require protection measures to be taken [2].

The indoor radon levels in the air were measured in 30 most frequently visited rooms (school, kindergartens, first-aid post, hospital, magistrate, living houses, etc.) in Yangiabad and in 18 similar premises in Charkesar.

Track detectors of the CR-39 type were positioned in selected rooms in Yangiabad and in Charkesar for five months.

The concentration of a radon in Yangiabad ranged from 70 to 350 Bq/m^3 (200 Bq/m^3 in the average). A significantly elevated Radon concentration level of 770 Bq/m^3 was measured in a shop constructed from local materials.

In Charkesar, the concentration of radon ranged from 80 to 390Bq/m^3 (with an average of 250 Bq/m^3). Significantly elevated levels were found in two private houses constructed from local materials; the radon concentrations were between 670 and 1410Bq/m^3.

According to the national regulations the average annual volumetric concentration of radon and progeny indoors must not exceed 80 Bq/m^3[3].

The annual effective exposure dose for a member of the public was calculated using the formula:

$$D = A_{Rn} * F * T * DCF, \text{ mSv/y}$$

where

$F = 0.4 - 0.5$ (F=0.5 was used in the calculation);
A_{Rn} = average value of the radon concentration, Bq/m^3;
$DCF = 9\ nSv/h*Bq*m^{3;}$
T = exposure time in the chosen room in hours;
T = 365*24=8760*0.6=5000 h, (0.6 is the fraction of time spent in the room). For a shop a time fraction value of 0.3 was assumed to be acceptable).

In Yangiabad, the effective exposure dose (LED) was calculated to be 0.9-4.0mSv/y (in average 3 mSv/y) and for rooms with high concentration of a radon an exposure of 5.4 and 19.2 mSv/y were estimated. As it was shown, at Yangiabad the effective annual exposure dose does not exceed the permissible value, with the exception of two rooms.

In Charkesar, the effective dose (LED) was 2.0-6.5 mSv/y (4.5 mSv/y, in average). In three rooms the effective dose was as high as 8.7, 8.8 and 13.5 mSv/y.

The results show, that the exposure dose of the inhabitants of Charkesar exceeds in some cases the exposure doses estimated for the inhabitants of Yangiabad.

Gamma dose rates were also measured at the same premises. The measured gamma dose rates in Yanghiabad were 0.2 to 0.4 μSv/h and in Charkesar 0.3 to 0.75 μSv/h.

RADIONUCLIDES IN WATER AND SOIL

As previously described, there are mine water drainage places at the site of the former Charkesar mine. The water draining from the mine was sampled for laboratory measurements. The volume of each water sample was 5 l. To prevent sorption of elements on the walls of the bottle the samples were acidified using high purity nitric acid.

The size of the soil samples was 1 kg. The soil was dried, ground, sieved and averaged by quartering. In the water from the draining mine shaft the analysis found:

5.2 Bq/kg of Pb-214;
4.0 Bq/kg of Bi-214 and
2.7 Bq/kg of Ra-226.

The concentration of radium-226 exceeds the regulated limit (0.5 Bq/kg) approximately 5 times [3]. The concentration of the radionuclides in the soil taken from the place where the mine water drainage occurs shows the following contaminants content (Table 1).

TABLE 1. RADIONUCLIDES IN THE SOIL, BQ/KG

Nuclide	Tl-208	Pb-212	Bi-212	Pb-214	Bi-214	Ra-226
Conc.	349	1100	1200	4900	4600	62800
Nuclide	Th-234	U-235	Pa-234m	Ra-223	Pb-210	
Conc.	22100	2700	73600	3900	15000	

The measurements show that the soil is contaminated and should be removed and relocated into an orderly prepared mine waste pile, which then would be properly remediated.

RADIONUCLIDES IN THE LOCAL PRODUCE

The content of radioactive and toxic elements in the locally produced foodstuff was also checked to assess whether there is a contribution to the exposure of the inhabitants of Yangiabad and Charkesar via ingestion. These measurements were necessary due to the fact that some of the food used in the local diet (fruit, vegetables, meat, milk, etc.) is produced on the sites of the decommissioned mines. The first step of these investigations was to determine what constitutes the typical daily diet in Yangiabad and Charkesar. Following the data on the composition of the diet (milk, bread, flour, pancakes, pasta, carrots, fruits, tomatoes, beet, radish, onion, cabbage, meat, water, etc.) the foodstuff was bought in the local shops and on the markets (bazaars). The model daily diet was then prepared and the components analysed using gamma spectrometry and instrumental neutron activation analysis. The estimated daily intake of radioisotopes is given in Table 2.

TABLE 2. DAILY INTAKE OF RADIONUCLIDES WITH FOODSTUFF, BQ

Nuclide	Yangiabad	Chorkesar
^{40}K	75 ± 17	70 ± 15
^{226}Ra	< 1.0	10 ± 3
^{238}U	< 2.0	7.0 ± 4

Table 2 shows that the intake of ^{226}Ra and ^{238}U within foodstuffs is significantly higher in Charkesar than in Yangiabad. This means that the inhabitants of Charkesar receive a significantly higher additional radiation exposure via ingestion.

Table 3 specifies the daily intake of all elements contained in the foodstuff. A further conclusion from Table 3 is that the daily intake of Cr, Fe, and Sb with the food in Yangiabad exceeds the ICRP recommendations [4]. In Charkesar, the intake of Cl, Mn, Cr, Fe is higher than the recommended limits. This is contrasted by a deficiency of Br, Co in the diet in Charkesar and deficiency of Mo in Yangiabad. The amount of U in the daily diet in Charkesar is approximately 50 μg, which is more than 10 times higher than in Yangiabad.

TABLE 3. ELEMENTS IN THE DAILY INTAKE OF FOOD

Element	Yangiabad	Chorkesar	Recommendation of the ICRP [4]
Ag, μg	12±3.0	6±1.0	
Ba, mg	0.8±0.2	0.9±0.2	
Br, μg	1660±100	1300±65	7500
Ca, g	0.8±0.02	0.6±0.02	1.1
Ce, μg	22±3.0	26±4.0	
Cl, g	5.2±0.2	6.9±0.2	5.2
Co, μg	25±6.0	24±6.0	300
Cr, μg	330±57	310±19	150
Cs, μg	8±0.6	5±0.4	
Fe, mg	22±3.0	20±1.2	14
Hg, μg	0.4±0.1	3±1.0	15
K, g	3.0±0.2	1.9±0.1	3.3
La, μg	22±3.0	26±9.0	
Mn, mg	3.8±0.08	6.0±0. 2	3.7
Mo, μg	125±6.0	290±20	300
Na, g	3.0±0.1	3.3±0.1	4.4
Rb, mg	2±0.2	1±0.1	2.2
Sb, μg	49±18	10±2.0	~50
Sc, μg	4±0.2	3±0.1	
Sr, mg	7±0.3	4±0.5	
Th, μg	5±0.1	4±1.0	
U, μg	< 4,0	48±4.0	
Zn, mg	9±0.5	10±0.8	13

CONCLUSIONS

- The results of our measuring campaign indicate that the uranium mining wastes at the decommissioned mine sites have a serious impact on the environment and possibly on the health of the population in the vicinity of the sites.
- Based on these brief investigations it can be concluded that the remediation of the former uranium mining sites is very important but the development of effective remediation plans requires additional investigations.
- In addition, it is essential to carry out a more complete study of the concentrations of radionuclides and toxic elements in the relevant media as well as investigate their behaviour of in the environment of the decommissioned mines and compare the data with the local health statistics.
- As shown in our earlier studies [5] it is necessary to include into the investigations a wider area than just the legacy sites because due to the dispersal of radionuclides and toxic elements usually a much larger area is affected than just the site of the former uranium mining.
- The present data pool should be complemented by additional types of samples, including bottom sediments, airborne particles, human biosubstrates (human hair), etc.

- For a more exact assessment of the risk associated with the former mining sites experimental studies of the leaching behaviour of the radioactive and toxic elements from the mine wastes by the river water would be very useful to derive better founded scientific conclusions regarding the consequences of a “natural” relocation of the mine wastes in form of mudflows into the close-by rivers.
- Of great importance should be the creation of a national system of the environment motoring near the mines
- Of vital importance is to have a wide exchange of ideas and results obtained among all Central Asian countries because of the similarity of the problems left behind by the former uranium mines and because of the cross border interconnection of the contaminated sites via rivers. To address these problems successfully requires an open and wide cooperation among these countries, which is best achieved within international projects.

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MOAB, UTAH, UMTRA SITE: THE LARGEST URANIUM MILL TAILINGS PILE TO BE RELOCATED IN THE UNITED STATES

D. R. Metzler
U.S. Department of Energy, Grand Junction, Colorado, United States of America

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Abstract

The U.S. Department of Energy (DOE) is tasked with cleaning up surface contamination and developing and implementing a ground water compliance strategy to address contamination resulting from historical uranium-ore processing at the Moab, Utah, remedial action site. During its years of operations, the facility accumulated approximately 12 million cubic yards (9.2 million cubic meters) of tailings and contaminated soils in an unlined pile about 750 feet (229 meters) from the Colorado River. DOE's preferred alternative is to relocate the tailings to an alternate site approximately 30 miles (48 kilometres) away from the river near Crescent Junction, Utah and to implement long term ground water remediation. Conceptual designs for the material handling, excavation, transportation, and the disposal cell have been developed. An interim action ground water extraction/injection system is currently in operation to reduce the contaminant mass in ground water discharging to the river.

INTRODUCTION

The Moab, Utah, site is a former uranium-ore processing facility located about 3 miles (4.8 km) northwest of the city of Moab in Grand County, Utah (Figure 1) and lies on the west bank of the Colorado River at the confluence with Moab Wash. Arches National Park has a common property boundary with the Moab site on the north side of U.S. Highway 191, and the park entrance is located less than 1 mile (1.6 km) northwest of the site. Canyonlands National Park is located about 12 miles (19 km) to the southwest.

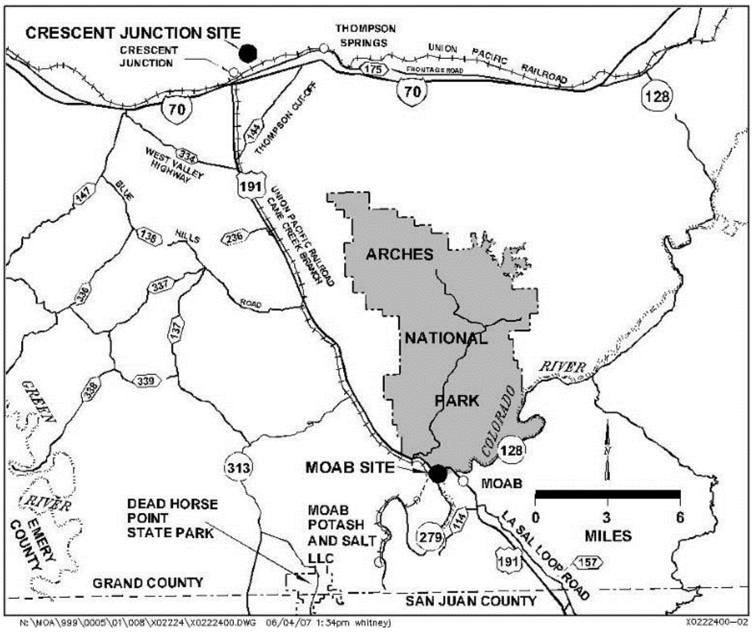

FIG.1. Location map of the Moab site and surrounding area.

During its years of operation, the facility accumulated approximately 16 million tons (14.5 tonnes) of tailings and contaminated soils. The tailings are located in a 130–acre (53-hectare) unlined pile that occupies much of the western portion of the site and is about 750 feet (230 meters) from the Colorado River. The pile was constructed with five terraces and consists of an outer compact embankment of coarse tailings, an inner impoundment of both coarse and fine tailings, and an interim cover of soils taken from the site outside the pile area. Debris from dismantling the mill buildings and associated structures was placed in an area at the south end of the pile and covered with contaminated soils and fill.

Ground water in the shallow alluvium at the site was contaminated by ore-processing operations. The Colorado River adjacent to the site has been affected by site-related contamination, mostly because of ground water discharge. The primary contaminant of concern in ground water and surface water is ammonia. DOE has identified two ammonia plumes associated with the site: a deep plume beneath the tailings pile and a shallower plume emanating from the toe of the tailings pile to the Colorado River. Ground water from the shallow plume discharges to the Colorado River and has a localized impact on surface water quality. Degradation of surface water quality is of concern because of potential effects on aquatic species in the area, particularly endangered species of fish.

To minimize potential adverse effects to human health and the environment in the short term, DOE instituted engineering controls and interim actions at the site. Controls include storm water management, dust suppression, pile dewatering activities, and placement of an interim cover on the tailings. Interim actions include restricting site access and monitoring ground water and surface water. An interim action ground water extraction/injection system was implemented to reduce the contaminant mass in ground water discharging to the Colorado River.

REGULATORY FRAMEWORK

The title to the Moab site was transferred to DOE in 2001 along with the responsibility for site cleanup in accordance with Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA). The act further requires that remediation of the site include ground water restoration. Ground water compliance and soil cleanup standards applicable to the Moab site are the U.S. Environmental Protection Agency (EPA) standards established in Title 40 *Code of Federal Regulations* Part 192 (40 CFR 192). DOE's Uranium Mill Tailings Remedial Action (UMTRA) Project was established to perform site cleanup and permanent disposal of uranium mill tailings according to the EPA standards.

Pursuant to the National Environmental Policy Act, Title 42 *United States Code* Section 4321 et seq., DOE prepared an Environmental Impact Statement (EIS) to assess the potential environmental impacts of remediating the Moab site. DOE analysed the potential environmental impacts of both on-site and off-site remediation and disposal alternatives involving both surface water and ground water contamination. Some government agencies and the public expressed concern about the potential effects of capping the contaminated materials at the site, a proposed alternative because of the uncertainty of river migration and the long term effects of contaminated ground water entering the Colorado River. For these reasons and other factors, the DOE preferred alternative is to relocate the tailings by railroad to an alternate site away from the Colorado River and to implement long term ground water remediation to address contamination that resulted from historical uranium-ore processing at the former millsite.

Title I of UMTRCA stipulates that DOE select a remedial action in concurrence with the U.S. Nuclear Regulatory Commission (NRC) and directs the NRC to license the disposal site for long term care. DOE has prepared a Draft Final Remedial Action Plan (RAP) that presents the general technical approach and design criteria to demonstrate compliance with the EPA standards. The RAP is the compliance document that requires NRC concurrence prior to relocating the tailings to the off-site location near Crescent Junction, Utah.

CONCEPTUAL REMEDIAL ACTION DESIGNS

Conceptual designs for the material handling, excavation, transportation, and the disposal cell have been developed. The conceptual design for the disposal cell is presented in the Draft Final RAP and establishes the technical performance basis to demonstrate that EPA standards are met for tailings stability, radon control, and water resource protection. The conceptual designs for the disposal cell layout, perimeter dikes, and cover components limit infiltration through the cover to a water flux rate of approximately 1 3 10^{-7} centimetres per second (cm/s). The disposal cell site is located in an arid desert, which receives an average of 9.1 inches (23.1 cm) of annual precipitation; pan evaporation rate is 60 inches (152 cm) per year. Most rainfall events are brief and intense, followed by rapid evaporation.

EPA standards for cleanup and final disposal of the tailings establishes a design objective for geologic and geotechnical stability for up to 1000 years to the extent reasonably achievable, and in any case, a performance period of at least 200 years. As a consequence, the disposal cell cover and erosional features are designed to withstand maximum credible earthquakes, probable maximum precipitation events, and probable maximum flood events.

Figure 2 shows the conceptual approach to isolation of the tailings from the ground water aquifer located 2400 feet (732 meters) below the site in the Dakota Sandstone Formation. The bedrock directly beneath the cell is Mancos Shale, which is composed primarily of mudstones that have a very low hydraulic conductivity, less than 2.4 3 10^{-8} cm/s. A minor quantity of ground water is located in fractures in the shale.

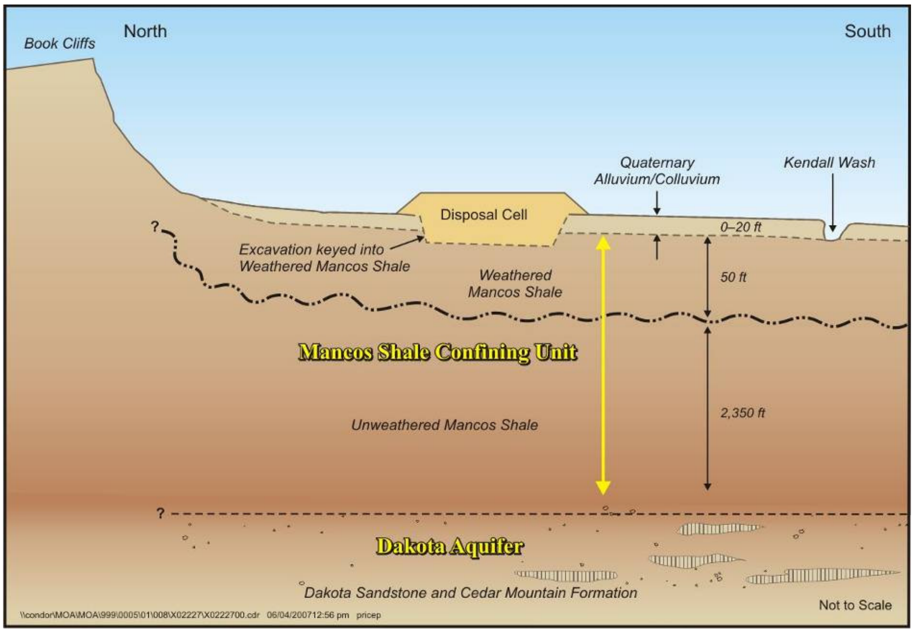

FIG.2. Conceptual approach to isolating tailings from ground water.

DOE’s analyses show the water in the shale to be very saline or briny, with total dissolved solids (TDS) concentrations greater than 23 000 milligrams per litre (mg/L). Radiocarbon dating indicates the water is at least 40 000 years old. Consequently, the ground water is believed to be connate and unconnected to the deeper regional aquifer. Vertical time for tailings leachate to potentially reach the Dakota Sandstone aquifer is estimated to take from 5860 to 58 600 years. Geochemical attenuation would probably lengthen the travel times for constituents such as ammonia and uranium.

The disposal cell will be constructed so that the bottom is built into the weathered top layer of Mancos Shale. Because of the overall low hydraulic conductivity of the shale formation and geologic isolation from the lower aquifer, no liner is required in the bottom of the cell. The combination of clean fill dike around the cell and placement of the cell bottom into the weathered zone forces the leachate into the weathered Mancos. This prevents the leachate from traveling faster horizontally through the upper colluvium layer and possibly daylighting in nearby drainage washes. In addition, the weathered zone of the Mancos Shale has a higher hydraulic conductivity than the lower, more competent material, which will also prevent leachate from building up in the cell. The approach provides a strategy that is very protective of human health and the environment.

The cover system over the tailings is designed to limit release of radon gas from the tailings, reduce infiltration, and provide erosion protection for at least the minimum design life, as stated. Two cover design alternatives were prepared during the conceptual design stage so that the DOE can weight the costs and benefits and pick the best value in their final design. The UMTRA checklist cover (Figure 3) contains a radon barrier with compacted material, interim cover of random fill, infiltration/biointrusion barrier of sandy gravel, frost protection layer, and rock erosion cover.

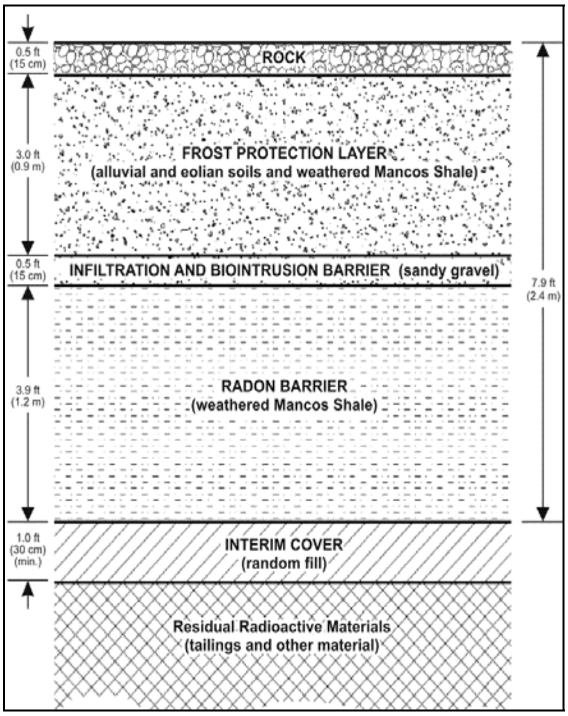

FIG.3. UMTRA checklist cover design.

The alternative cover uses a monolithic zone of uncompacted random fill in lieu of the radon barrier and frost barrier. This design calls for a cover thickness greater than that of the checklist cover but accommodates wasting of soil if the earthwork cut exceeds fill in the overall cell design. Both cover designs have been built on other uranium mill tailings disposal cells in the United States and have a proven record of performance. Vegetation may be incorporated into the cover design; however, it is not required to demonstrate compliance with the standards.

The rock top layer is designed to be a maximum slope of 2% with an average rock diameter (d50) of 2 inches (5 cm). The north side of the cell will intercept all the drainage coming off the Book Cliff range to the north, which comprises a 0.5–square-mile (1.3–square-kilometer) basin. The resulting peak flow from a probable maximum flood is 5,859 cubic feet per second (165 810 litres per second). Because of the erosional nature of the colluvial soils above the cell, rather than build a typical trapezoidal rock channel, DOE developed a channel design that would silt up during smaller rainfall events and erode during larger events. To prevent undermining or scour beneath the toe of the disposal cell, a 6–foot (1.8 m)–deep trench of 20-–nch (51cm)-diameter rock will be constructed.

One of the biggest construction challenges will be moisture conditioning of the fine fraction of tailings material (slimes) located in the tailings pile. Water content (by dry weight) in the pile varies from 10% in the sands to over 100% in the slimes. Since vibration of the material during transportation will result in separation of water and possibly leakage from containers, the slimes will have to be mixed with sands and possibly air dried before loading and shipping. In DOE's Record of Decision, it was decided to move tailings primarily by rail to the disposal cell located 30 miles (48 km) to the north. The other challenge will be to get the tailings from the current site, across a state highway, under high voltage power lines, and up to a rail spur that sits 200 feet (61 m) vertically above the pile. The two primary methods studied to date are the simpler method of containers carried by truck on a haul road up to flat cars on the rail, or conveyor to gondola cars. There are numerous concerns with the conveyor option because of the variable nature of the material, the steep slope, the amount of debris in the pile that will have to be screened, and overall reliability of mechanical systems. Because of contract strategies, DOE has not decided on the final method for handling and moving tailings.

GROUND WATER CONTAMINATION FROM MILLING OPERATIONS

Ground water at the site occurs mostly in alluvial sediments that may be as deep as 394 feet (120 m) or more. TDS concentrations in the alluvial ground water vary naturally from slightly saline water (1000 to 3000mg/L), to those categorized as moderately saline (3000 to 10 000mg/L), very saline (10 000 to 35 000mg/L), and briny (> 35 000mg/L). The primary source of the slightly saline water, which is found only in the shallowest parts of the saturated zone, appears to be ground water discharge from bedrock aquifers that subcrop near the northwest border of the site and north of the tailings pile. Brine waters dominate the deepest parts of the alluvium and are attributed to chemical dissolution of the underlying Paradox Formation, a large and relatively deep evaporite unit that has been deformed to create a salt-cored anticline aligned with and underlying the Moab Valley.

During milling operations, the tailings pond contained fluids with TDS concentrations ranging from 50 000 to 150 000 mg/L. Because these salinities exceed 35 000 mg/L, they had sufficient density to migrate vertically downward through the freshwater system and into the brine. This downward migration of the tailings pond fluids into the saltwater system is believed to have created a reservoir of ammonia that now resides below the saltwater interface. This ammonia plume below the interface probably came to rest at an elevation where it was buoyed by brine having a similar density. Under present conditions, the ammonia plume beneath the saltwater interface represents a potential long term source of ammonia to the freshwater system. The conceptual model presented in Figure 4 illustrates the ammonia source at the saltwater interface (basal flux), the legacy plume, and seepage of ammonia from tailings pore fluids.

DOE identified two ammonia plumes associated with the site: a deep plume beneath the tailings pile and a shallower plume emanating from the toe of the pile to the Colorado River. Although ammonia has no EPA standard in 40 CFR 192, it occurs at concentrations significantly greater than natural background, is the most prevalent contaminant in the ground water, and is the constituent of greatest ecological concern that is discharging to the Colorado River.

The highest ammonia concentrations in surface water samples are detected in samples collected in backwater areas adjacent to the site. Ammonia levels have been of concern since ammonia was first detected in river samples, largely because of the designation of this segment of the Colorado River as critical habitat for the Colorado pikeminnow (previously referred to as Colorado squawfish) and three other endangered fish species (razorback sucker, bonytail, and humpback chub). Pikeminnow favor slow-moving backwater areas of the river as nursery habitat for young-of-the-year fish.

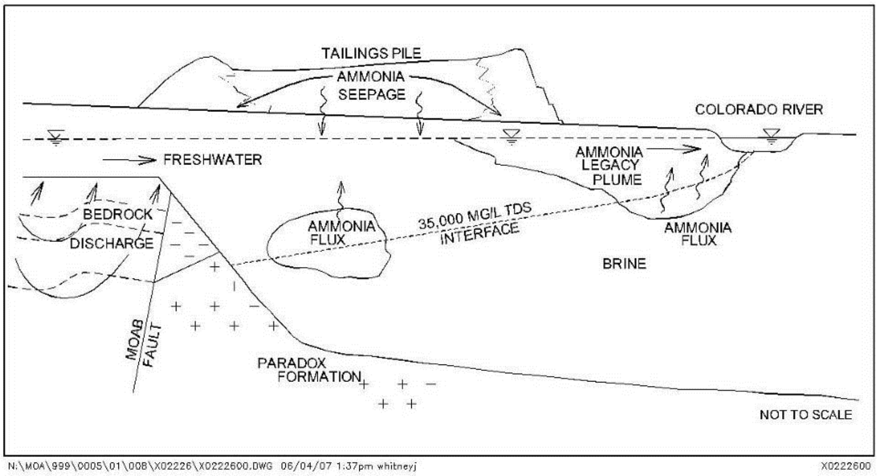

FIG.4. Conceptual model of seepage of ammonia from the tailings pile.

GROUND WATER INTERIM ACTION

A well field has been built in four phases since 2001. Ground water extracted from the shallow aquifer from the well field is pumped via pipeline to a solar evaporation pond for treatment (Figure 5).

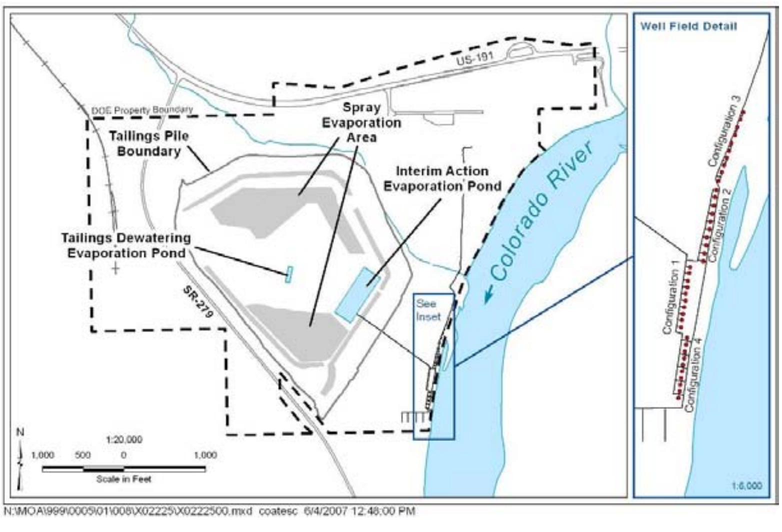

FIG.5. Locations of the interim action systems at the Moab site.

The evaporation pond covers approximately 4 acres (1.6 ha) and was constructed outside the 100–year floodplain on top of the tailings pile. In addition to the evaporation pond, a 17–acre (6.8 ha), land-applied spray evaporation system was installed in 2004 to enhance evaporation of ground water pumped from the interim action extraction wells by using a sprinkler system installed on top of the tailings pile next to the evaporation pond. The sprinkler system consists of micro-spray nozzles on 25–foot (7.6 m) centres. The system was expanded to include an additional 11 acres (4.4 ha) in 2005. The combined 28 acres (11.2 ha) of sprinklers operate in conjunction with the existing evaporation pond, which has more than doubled the capacity of the existing interim action. The system is designed to evaporate the water before it infiltrates the tailings pile and to provide dust suppression.

CONCLUSIONS

In October 2001, DOE was tasked with the requirements to clean up surface contamination and develop and implement a ground water compliance strategy to address contamination that resulted from historical uranium-ore processing at the abandoned Moab millsite. The Moab site is the largest uranium mill tailings pile to be relocated in the United States.

DOE instituted environmental controls and interim actions at the site to minimize potential adverse effects to human health and the environment in the short term while a draft EIS was being prepared to evaluate long term remediation alternatives. The DOE preferred alternative is to relocate the tailings to an alternate site 30 miles (48 km) away from the Colorado River and to implement long term ground water remediation.

The interim action ground water system will continue to operate and may eventually become part of the final ground water remedy. Monitoring data are currently being collected to demonstrate the effectiveness of the system prior to design and construction of the long term ground water strategy.

A conceptual design of the new disposal cell has been prepared and presented to the regulators. The design uses a 2400–foot (732 m) thick geologic unit of shale under the site to isolate the tailings leachate from a regional aquifer. Two cover designs were prepared that incorporate basic features to limit radon flux, minimize infiltration into the cell, and provide erosion protection. The final cell design will be based on economics of developing rock sources, balancing earthwork cut and fill, and haul distances.

THE WASTE ROCK RELOCATION PROJECT AT THE RONNEBURG MINE SITE: A TECHNICAL AND TECHNOLOGICAL OVERVIEW*‡‡

M. Paul, F. Wille
Wismut GmbH, Chemnitz, Germany

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Abstract

The most prominent project of the mine closure program at WISMUT's Ronneburg mine site has been the Waste Rock Relocation Project, which comprised the relocation of about 131 Mm^3 of waste rock and associated contaminated material from demolition and area clean-up to the worked-out Lichtenberg open pit mine. General rehabilitation planning at Ronneburg called for waste dumps located south of the A 4 motorway to be relocated into the Lichtenberg open pit while waste piles located to the north of the A 4 motorway had to be jointly remediated at the Beerwalde site. The relocation project started by the end of 1990, and the actual relocation activities ceased in early 2008. Final remediation measures at the Lichtenberg backfill such as cover construction, re–vegetation and the construction of access roads and dewatering facilities will be ongoing until 2010.

Geochemically controlled and compacted placement of waste rock into three different zones (A, B, C) within the open pit in conjunction with specific measures such as alkali addition to material already acidified proved to be an optimum remedial strategy for the ARD producing waste rock, leading to a spatial concentration of waste, consequently minimising the surface of contaminated areas, limiting contaminant release and radiological exposure, and also resolving pre-existing dangers caused by the abandoned open pit mine.

The master plan for the relocation project was based on extensive investigation programs throughout the early 1990s. The successful implementation of the project, however, had been in the hands of an efficient project management unit.

After 17 years of remediation activities the reclaimed Ronneburg mine site is now offering a multitude of possibilities for a prosperous regional development, as it has been demonstrated by the Federal Horticultural Show BUGA 2007, which had been partially implemented across reclaimed former mining areas, in the immediate vicinity of the former Lichtenberg open pit mine.

INTRODUCTION

Since 1991 WISMUT GmbH has been carrying out the closure of the entire East German uranium mining industry. Among the former mine sites the Ronneburg mining district which produced from both underground and open pit operations was the most important with a production of approximately 113 kt U. The Ronneburg site is located in Eastern Thuringia about 10 km east of the town of Gera. Uranium mining at this site started in 1951 and ceased in 1990. Being the largest of three local open pit operations, the Lichtenberg open pit was mined between 1958 and 1977. This open pit covered an area of about 160 ha with a maximum depth of 240 m and a total mined volume of 160 Mm^3.

Following termination of the mining operations in 1990 remedial action was soon initiated. The mining legacy at Ronneburg consisted of (1) a large and complex underground mine to be closed, (2) production facilities to be demolished and operational areas covering

1670 ha to be cleaned-up and prepared for reuse, (3) waste rock material with an overall volume of about 200 Mm^3 to be properly remediated, and finally (4) the worked-out Lichtenberg open pit mine to be closed and stabilized.

As a consequence of these site conditions is was decided by the end of 1990, that the huge majority of the waste rock will be backfilled into the Lichtenberg open pit [1]. Due to its size and complexity, this Waste Rock Relocation Project at the Ronneburg site became the most important single remediation project of the entire WISMUT remediation program.

Waste relocation started by the end of 1990, and it was completed in early 2008. The paper gives an overview on this remediation project, focussing on the conceptual outline and discussing main technical and technological aspects.

SITE SITUATION AND REMEDIATION STRATEGY

At the end of mining in 1990, dumped mine wastes from the open pit and the five individual underground mines at the Ronneburg site[1] amounted to about 200Mm^3, situated at 17 single locations (see also Table 4). The two biggest piles of the district, the so-called Absetzerhalde (70 Mm^3) and the Nordhalde (31 Mm^3), were both resulting from open pit mining at the Lichtenberg pit. Most characteristic for the Ronneburg site were, however, the conical piles of Reust (6.4 Mm^3) and Paitzdorf (7.9 Mm^3), well-known landmarks with heights of more than 100 m each. About 76 Mm^3 of mine waste had been deposited within the Lichtenberg open pit before 1990, known as Inside dump (64 Mm^3, mainly resulting from the extension of the open pit between 1972 and 1977), and Schmirchau balcony (12 Mm^3, containing the waste rock from the neighbouring Schmirchau deep mine).

The wastes comprised for the most part black shales, limestones and diabases with a high tendency to AMD due to pyrite/marcasite contents of up to 5%, resulting in acid to neutral, highly mineralized seepage waters with significant contents of iron, heavy metals (such as manganese, nickel, copper, zinc, cobalt, cadmium), arsenic, uranium, sulfate, and magnesium [2, 8]. Therefore, the most crucial environmental problems of the waste rock dumps, which were mainly uncovered and freely accessible, resulted from the impact to ground and surface water resources. Besides that, a need for remedial action arose from the perspective of radiation protection, due to geotechnical reasons, but also to ensure a safe and sustainable after-use of the dumps.

Based on intensive cost-benefit-analyses of different remediation options the relocation of the waste rock into the Lichtenberg open pit was chosen as the preferred remediation option for more than 90% of the waste rock. The main arguments for this remediation strategy can be summarized as follows:

- Spatial concentration of the waste rock to minimize overall infiltration, and to optimize long term liabilities such as water treatment, monitoring and after-care, reducing the area impacted and increasing the area of land returned to productive use;
- Safe closure of the worked-out pit, stabilization of the pit walls and prevention of a highly contaminated pit lake to develop in ultimate vicinity to the community of Ronneburg after mine flooding;
- Minimization of the mobility of the contaminants of concern by means of geochemically controlled relocation (separation) and alkali amendment;

[1] Schmirchau including Lichtenberg, Reust, Paitzdorf, Beerwalde and Drosen

— Limitation of the rate of contaminant transport from the backfill into the groundwater due to high compaction of the relocated waste rock, combined with the principle of by-passing of the groundwater flow around the backfill body via a multitude of open drifts of the flooded underground mine, and finally
— Cost optimization.

Since the Gessenhalde represented a significant radon source, relocation work on this former low grade ore heap leach operation was initiated before a clearly defined reclamation plan was developed. This work, however, provided some lead-time to allow optimization of the reclamation plan for the remainder of the waste rock dumps. Intensive investigations were undertaken between 1992 and 1996, resulting in a general backfill concept.

Core of this concept was the targeted placement of waste rock within the pit to allow the minimization of contaminant release into the groundwater (Figure 1). Acid or potentially acid generating (class A or PAG) material was mixed with quicklime and placed in the deepest zone of the open pit which will be watersatured by rising ground water and hence become anoxic after mine flooding has been completed (saturated anoxic zone A). Non acid generating (class C or NAG) material, however, was disposed of in the uppermost, so-called C-zone of the backfill (oxidation zone). Class C material is to consume incoming oxygen by sulphide oxidation and, at the same time, to impede seepage acidification due to neutralisation. The minimum thickness of zone C was established to be 10m [3, 4] Class B material (uncertain behaviour in terms of net-acidification, UC) which includes mixtures of class A and class C material had to be relocated into the intermediate Zone B above the groundwater table (unsaturated anoxic zone).

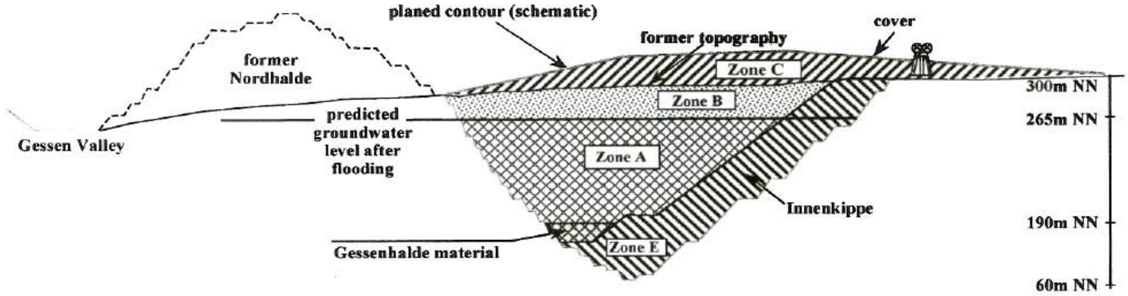

FIG.1. Principle of the backfilling strategy for the Lichtenberg open pit (taken from [5]).

Since three of the waste rock dumps (Beerwalde, Drosen, and Korbußen with a total volume of 8.4 Mm^3) were located at quite a far distance to the open pit and beyond a major highway (federal motorway A 4), relocation to the Lichtenberg pit was not a realistic scenario, both for cost and feasibility reasons. Therefore, as an alternative, it was decided to concentrate the mine waste of these three dumps at the location of the Beerwalde waste rock dump.

OUTLINE OF THE WASTE ROCK RELOCATION PROJECT

Due to the strong interrelationship between waste dump remediation, open pit closure, site clean-up and mine flooding the waste rock relocation project took a key position within the entire remediation strategy for the Ronneburg mine site soon after the start of the remediation works.

As a consequence of that, the outline of the master plan for the waste rock relocation project had to take into account a multitude of factors and boundary conditions. The most important one was the mass balance of waste rock and other remediation material such as contaminated soil, debris etc. to be relocated and disposed of, in comparison to the open volume available in the open pit. According to the zone concept described above this mass or volume balance had to be prepared not only for the entire pit, but also for each different zone.

While the volumes of the disposal zones were more or less clearly defined by the planned final surface contour of the backfill, the design thickness of the C-zone and the expected groundwater level after mine flooding, extensive investigations were necessary to come up with appropriate separation criteria for the waste rock itself. These criteria were established as the result of a broad investigation program carried out between 1992 and 1996. The investigations included the review of all available historical, mineralogical and geological informations, drilling of boreholes, excavation of test pits, chemical and soil physical analyses, static laboratory tests as well as kinetic column and lime addition tests [3, 6, 7].

The relocation control program applied is summarized in Table 1. Acid base accounting (ABA) on drill core samples was chosen for the long term planning of waste dump relocation, since this test allows rapid assessment of the ARD risk from sulphide-bearing waste. Due to the high variability of ABA data within the Absetzer- and Nordhalde, block models based on Kriging were prepared for both dumps.

Since the spatial variability of material properties could not be ascertained in sufficient detail from drilling data obtained on a 100m grid for the purpose of waste segregation, long term planning was supported by a program of short-term excavation control. Under this program, test pit samples were taken on a 25 m grid from the excavation lift one to three months ahead of relocation (Figure 2). The material was then classified by a combination of paste and NAP pH/conductivity as outlined in Figure 3. Due to their simplicity, paste and NAP tests, calibrated against ABA data and kinetic test results, proved to be well suited to provide readily available guidance for short-term excavation control. Quality control samples were taken directly off the mining face to confirm material classifications and to allow correction of the short-term plan where necessary.

Material excavation was performed in 10m slices as a combination of ripping/ pushing by a dozer and loading at the toe of the mining face using one front-end loader per excavation site, as outlined in Figures 4 and 5.

TABLE 1. SUMMARY OF THE RELOCATION CONTROL PROGRAM

Objective	Data Basis	Sample Classification	Interpretation
Long term planning (volume estimates, relocation plan)	Drilling	A: NP/AP < 1 B: 1 < NP/AP < 2 C: NP/AP > 2	Kriging and hand interpretation
Short term planning (relocation control, lime application control)	Test pits (25x25 m grid)	see Figure 3 and Table 2	Hand interpretation
QA/QC of C-Material Relocation (Nordhalde, Absetzerhalde)	Face samples (3 per 50 m face)	see Figure 3	Control charts and tables
QA/QC of Relocation of Halde Reust and Paitzdorf	Composite samples (one per 50,000 m^3)	Confirmation of class C: NP/AP > 2	Control charts and tables
QA/QC of B- and C-Zone	In-pit composite from 5 pits per day and disposal section	see Figure 3	Control charts and tables
QA/QC of A-Zone	In-pit composite from 5 pits per day and disposal section	Paste conductivity < 6000 µS/cm	Control charts and tables

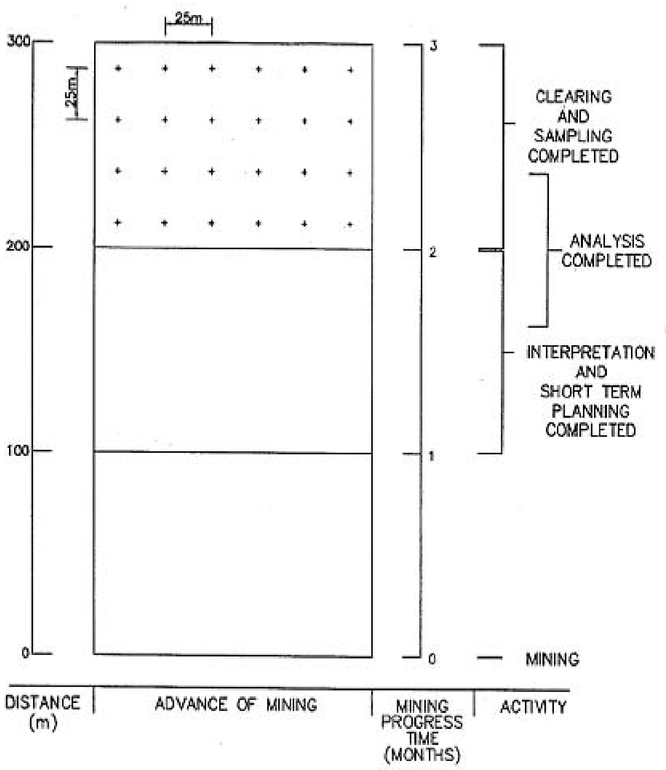

FIG.2. Schematic plan view of a 10m slice of an excavation area at the front end of the relocation chain: Sampling, interpretation and short term planning in advance of the waste rock relocation [8].

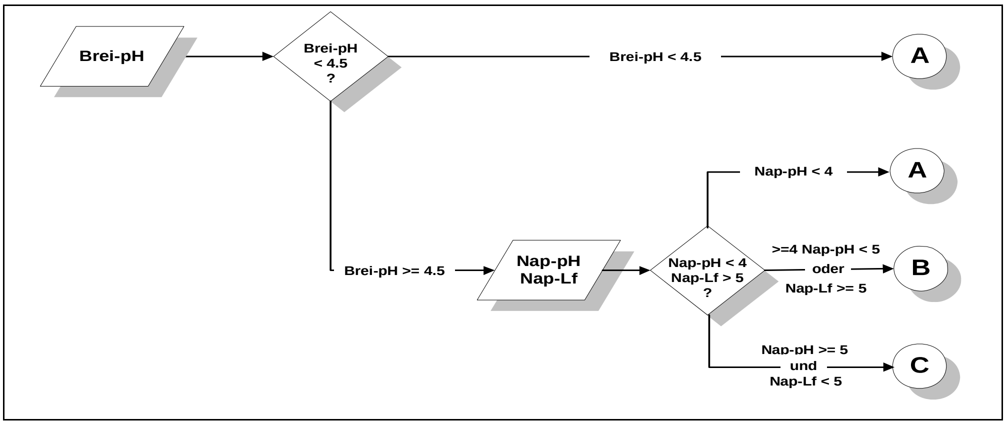

FIG.3. Decision protocol for waste classification based on paste and NAP-test on test pit samples from the excavation slice, 25 m grid (taken from [4]), as used for the relocation of Absetzerhalde and Nordhalde. Delineation of relocation segments was performed according to the following dilution criteria: Segments containing > 70- 80 % of class A samples must be relocated to zone A; Segments containing > 80 % of class C samples and < 10 % of class A samples must be relocated to zone C; Segments which do not fulfill any of the above criteria must be relocated to Zone B. Explanation: Brei = paste, Lf = conductivity.

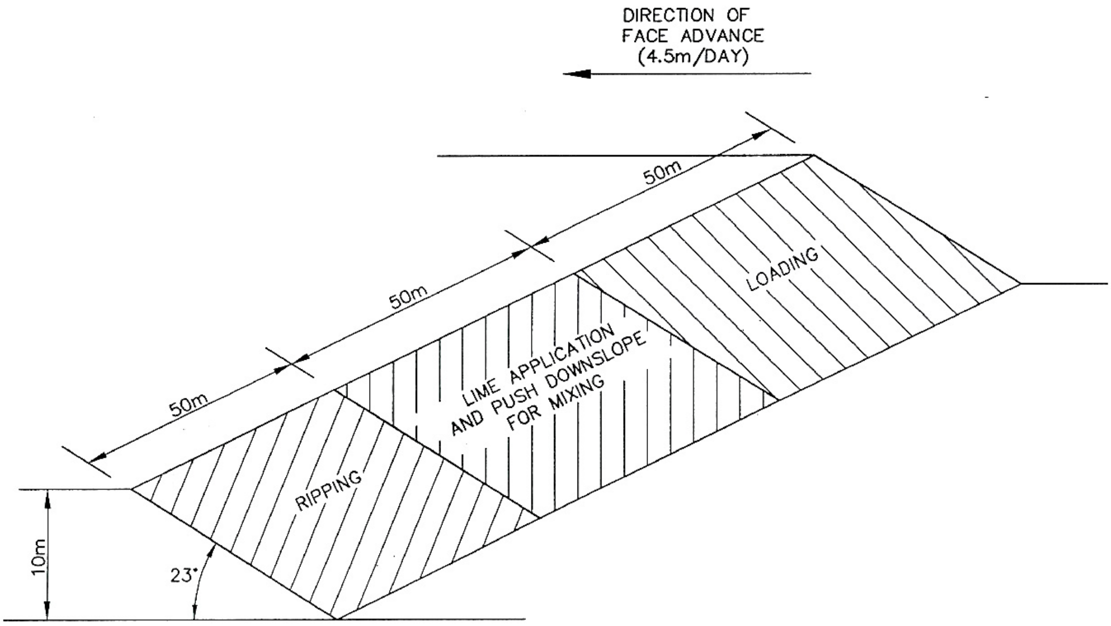

FIG.4. Schematic of the excavation technology, perspective view (SRK,1995).

Quicklime addition to zone A material was performed at the excavation front in order to guarantee optimal mixing with the waste rock. Dozers were used to push the lime together with the waste rock down-slope at an angle of about 22° and the ensuing action provided effective blending. The lime dosage was adjusted according to the paste conductivity of the waste rock in the section to be removed (Figure 3 and Table 2). The average lime addition rate to A-material was in the order of 1–3 kg CaO/tonne.

TABLE 2. EQUATIONS APPLIED FOR THE DETERMINATION OF THE RATE OF QUICKLIME ADDITION TO ZONE A MATERIAL

Paste conductivity, pc (mS/cm)	CaO addition (kg CaO/ tonne of waste rock)
0 – 2	0.35
2 – 4	0.858 * pc – 1.36
> 4	1.03 * pc – 2.05

Compacted placement of the waste rock within the pit was realised in 0.6 to 1m lifts by controlled truck traffic. The elevated degree of compaction (>95% proctor density) will prevent to a large extent groundwater and gas flow through the waste rock (k_{sat} 10^{-6}…10^{-8} m/s).

FIG.5. Waste rock excavation. Technological sequence with Dozer D11R, Front-end loader CAT 992H and haul truck CAT 785. Relocation of Halde Paitzdorf, June 2006.

Design planning of the final backfill contour required special attention, since the total volume of waste rock to be relocated was not exactly known at the beginning of the operations, chiefly due to the limited knowledge about the contour of the footprint of some of the huge dumps, but also since the amount of additional contaminated soil to be excavated from the footprint area could only be estimated very roughly before its exhumation. Therefore, the design contour had to be robust to mass deficiencies of some million cubicmeters, and it had to be steadily refined as the remediation works proceeded.

The most significant change in the overall design resulted in 1997 from the decision to also relocate the Nordhalde, which was primarily scheduled for in situ-stabilization, to the pit. As a consequence of that, about 8 Mm^3 of class A material had to be relocated into the B-zone of the backfill. To ensure the safe enclosure of its contaminant potential, this class A material had been underlain by an in-pit geochemical barrier, constructed across the entire part of the filling body, consisting of mixed power plant ashes with a sufficient capacity to neutralise acidic seepage and effectively attenuate pollutants by sorption [9].

FIG.6. Lichtenberg open pit partially backfilled, with disposal areas for material A (foreground, bottom of the pit), B, and C (background), and ongoing relocation of the Nordhalde (background right). Situation in 1999.

Subsidence due to settlement of the backfill had to be taken into account, since the internal dump and the Schmirchau balcony were dumped during active mining, without any compaction. Another important feature for the design of the final contour of the backfilled pit consisted in the outline of the dewatering system. Targeted routing of access roads for maintenance and care accompanied by drainage ditches led to significant cost savings for technical measures necessary for flood protection of the downstream areas, especially for the community of Ronneburg.

The geochemically controlled waste rock relocation including the zone concept could only be realised using mobile haulage equipment of sufficient capacity. The project management had to permanently adjust the performance indicators of waste rock excavation, transport and pit disposal, regardless of any changes in the transport distances, in the gradients of the transport ramps, in the number of excavation and disposal locations or referring to the weather conditions.

The major challenge for the project management unit, however, consisted in the permanent implementation of the idealized zone concept (ABC) within the backfilled pit. In order to avoid phases of shortage of appropriately classified waste rock, alternative excavation and disposal sites had to be available at the front and the back end of the relocation cycle. Therefore, several dumps had to be relocated in parallel, and alternative disposal locations within the different zones of the pit had to be provided (Figure 6). The latter proved to be somewhat difficult to realize due to the limited space and the necessary compliance with the given constraints in time and budget.

The relocation project was accompanied by intensive engineering and QA/QC-measures. About 90 000 geochemical tests (paste and NAP/NAG-tests, chemical analyses) were performed for relocation control and QA/QC (see Table 1), and also ca. 5000 tests for compaction control at the disposal sites. Water management included the construction and operation of 140 000 m^3 of process water reservoirs, in order to supply the entire technological chain with sufficient water for dust control, but also to prevent any inadvertent discharge of contaminated surface and process waters to the receiving streams as a result of rainstorm events.

A crucial element within the project was the design of an optimized soil cover to be placed on top of the backfilled mine wastes over an area of 220 ha. As a result of comprehensive studies and investigations, a combined cover of cohesive soil material from on-site excavation (thickness 1.6 m) overlain by a 0.4 m thick storage layer to restore natural soil functions for revegetation was derived and permitted for construction [9]. Under this approach mature cover material from the Nordhalde and Absetzerhalde waste rock dumps, which was separately excavated during the relocation operation and deposited at an interim storage site, was scheduled to be used for the lowermost 1.6 m of the final cover, leading to tremendous cost savings. Together with hydraulic measures, this type of cover is to meet any legal requirement in terms of radiation and water protection, geotechnical stability, erosion control and reuse. The predominant after-use of the entire object will be forest.

The entire planning and permitting process of the Lichtenberg waste rock relocation project had to be escorted by an Environmental Impact Assessment. Due to the proximity of residential areas the main aspects to be considered included noise, dust, gas emissions and vibrations, in addition local climate, flora and fauna, emissions to ground and surface water and landscape aesthetics.

TECHNICAL IMPLEMENTATION AND PROJECT STATUS

Between 1990 and 2008 a total volume of 131 Mm^3 of waste rock and related remediation material had to be relocated; the annual relocation capacity was about 10 Mm^3 between 1996 and 2006. In 1993/1995 two fleets of heavy machinery were purchased to guarantee the technical implementation of the entire relocation project within the time constraints envisaged. Both fleets were consisting of up to 65 individual pieces of machinery, including heavy haul trucks (capacity 50/60/96/136 t), front-end loaders, dozers, motorgraders, and water trucks. During that time the Ronneburg waste rock relocation project was operating the biggest fleet of its kind in Europe (Table 3).

TABLE 1. TECHNICAL EQUIPMENT USED FOR THE WASTE ROCK RELOCATION AT RONNEBURG, REFLECTING THE SITUATION BETWEEN 1999 AND 2005

Number	Type		Aim	Tare weight (t)	Capacity (m^3)	Power (HP)
4	Dozer	CAT-D11N	Ripping/ pushing	97	34	744
2	Dozer	CAT-D11R	Ripping/ pushing	102	34	862
2	Front-end loader	CAT 994	Loading	177	18	1355
2	Front-end loader	CAT 990	Loading	75	9.2	648
11	Haul truck	CAT-785B	Transport	95	78	1399
5	Haul truck	CAT-773B	Transport	38	34	692
6	Haul truck	CAT-775D	Transport	44	42	720
2	Dozer	CAT-D9R	In-pit placement	48	16.4	411
1	Wheel Dozer	CAT-825G	In-pit placement	32	4	315
4	Grader	CAT-MG24H	Maintenance of transport routes	59	-	500
2	Grader	CAT-MG16H	Maintenance of transport routes	24.7	-	285
4	Water truck	CAT-773B	Dust control	40	50	692

The typical annual transport distance amounted to about 2 million km, at a daily transport capacity of about 40 000m^3 and a diesel consumption rate of 50 000 litres/day. Between 2003 and the end of the relocation works in 2007/08 the entire fleet was operated with biodiesel, both for cost and environmental reasons. Haulage roads for the dump trucks were generally built with waste rock material. Differences in altitude were bridged by sloped ramps of a maximum of 6%. The mine site topography allowed a haulage road design that enabled loaded trucks to use for the most part horizontal or sloped roads. The building material for the roads and ramps was hauled by trucks, graded and placed by dozer and compacted with haul truck traffic. Motorgrader were used for haul road maintenance. Permanent spraying of haul roads with water was the most important measure to control environmental impact from haulage (dust control). Spraying of haul roads was ensured by mobile means (water trucks). The truck fleet operated in two daily shifts of 8 h. Refuelling and small repairs were performed between the first and second shifts (1 hour break), while regular maintenance was carried out during the third shift.The entire project history is summarized in Table 4. Waste rock relocation started at the end of 1990 with the construction of the main transport ramp down to the bottom of the open pit. This ramp was constructed from waste rock of the Gessenhalde, which was removed first as an emergency measure, justified by the high risk potential of this dump.

After the relocation of the Gessenhalde had been completed using the so-called “small fleet”, which was chiefly characterized by 11 heavy haul trucks (CAT 773B) with a capacity of 50t each, the relocation of the Absetzerhalde, the biggest waste rock dump to be remediated under the entire WISMUT project, started in 1995, using an extra fleet of another 11 haul trucks (CAT 785B with a capacity of 136 t each) accompanied by front-end loaders, dozers and service equipment (so-called “big fleet”), which was put in service in the same year.

The excavation of the Absetzerhalde was characterized by some specific features, which made its relocation quite difficult and complex, since the dump had also been operated as a landfill site before 1990, used for the disposal of different types of both non-hazardous and hazardous wastes. Before the actual waste rock relocation could start, these solid and liquid wastes, which were deposited at the uppermost plateau of the dump, had to be separately relocated, chiefly to a new landfill site. This landfill site (volume ca. 1.0Mm^3) was designed, permitted and constructed between 1996 and 2002. Another unforeseen problem arose from the existence of a significant portion of oil contaminated waste rock (87 500 t on an area of 9000 m^2) which came across during the excavation works in autumn 1995, preventing some 1.3 Mm^3 of A-material from relocation. For this material, separate disposal options had to be worked out. The most contaminated parts of the material (petroleum-derived hydrocarbons > 30 g/kg) had to be immobilized and disposed of in the new landfill. Material with a lower degree of contamination was pre-treated in a bio-conversion facility, in order to degrade the organic carbon compounds down below the disposal limit (1 g/kg), prior to the relocation of the material into the pit [10].

TABLE 4.THE PROJECT AT A GLANCE: SYNOPSIS OF THE INDIVIDUAL WASTE ROCK DUMPS AT THE RONNEBURG MINE SITE AND THE CORRESPONDING REMEDIATION OPTION (RL = Relocation to the Lichtenberg open pit, RB = Relocation to Halde Beerwalde, I = In-situ stabilization, * = dumped within the Lichtenberg pit before 1990, no substantial remediation activity under the waste rock relocation project)

Waste rock dump	Volume, M (Mio. m^3)	Area (ha)	Active dumping period	Remediation option	Relocation/ remediation period
Absetzerhalde	70.1	224.7	1959-1970	RL	1993-2006
Innenkippe (Internal Dump)	64.0	*	1964-1989	*	-
Nordhalde	31.3	83.9	1962-1972	RL	1998-2003
Schmirchau Balcony	12.0	*	1964-1989	*	-
Halde Paitzdorf	7.96	24.9	1966-1992	RL	2006
Gessenhalde	7.6	28.7	1971-1978	RL	1990-1995
Halde Reust	6.4	20.5	1956-1990	RL	2004-2007
Halde Beerwalde	4.5	23.9	1977-1991	I	1997-2003
Halde Drosen	3.5	22.8	1982-1991	RB	1997-1999
Halde 370	1.4	6.0	1958-1989	RL	2003
Halde 4	0.9	7.8	1959-1964	RL	2006-2007
Halde Korbußen	0.4	4.1	1981-1989	RB	2000-2001
Halde 377	0.42	2.9	1956-1966	RL	2004
Halde 381	0.4	6.2	1961-1977	I	2004
Diabashalde	0.16	1.2	1971-1972	RL	2002
Schutzdamm	0.15	2.0	1967	RL	2007-2008
Schf 12/13	0.016	0.3	1952-1954	RL	1997

In 1998 the relocation of the Nordhalde was initiated and forced thereafter, since its 84 ha of footprint area were designated to host parts of the exhibition area of the Federal Horticultural Show to be held in 2007 (BUGA), after complete waste rock relocation, site clean-up and landscaping according to the plans for the BUGA exhibition. As a consequence of these specific boundary conditions, the Nordhalde removal was given first priority, so that it could be completed in early 2003.

In parallel to the ongoing relocation activities at Absetzerhalde and Nordhalde, the former Drosen and Korbußen waste rock piles, situated north of the federal motorway A4, were transported to the existing Beerwalde waste dump site, using parts of the "small fleet" (Figure 7). The activities started in 1997 and were finished in 2001. The Drosen waste dump (3.5 Mm^3) was relocated with excavators, 50 t–trucks and dozers. The haulage road to the Beerwalde site was built of Drosen waste rock and had a total length of 1750 m. The haulage capacity was estimated at some 10 800 m^3/d for a fleet of 10 trucks (50 t) and for a fleet of 6 articulated dump trucks (36 t) for dump base removal at 4660 m^3/d. A motor grader was used to ensure permanent trafficability of the haulage road and the transverse slope required for smooth precipitation runoff. During the haulage operation, run-off was collected and diverted to a settling pond at the Drosen site. Direct relocation of the Drosen waste pile took 13 months or some 300 working days, respectively, without construction and removal of the haulage road nor the excavation of the dump base. At the Beerwalde pile the waste rock material was placed in lifts of 0.6 m thickness and compacted with haul truck traffic (50 t). Following complete relocation of the Drosen dump, the Korbußen dump was also relocated to the Beerwalde site. Finally the entire new Beerwalde dump with a total volume of 8.8Mm^3 (including some 400 Tm^3 of contaminated soil) was covered with a two-layer cover system consisting of a 0.4 m thick compacted sealing layer overlain by 1.5 m of recultivation layer, and then re-vegetated. The Beerwalde cover system, according to model calculations confirmed by preliminary monitoring results, will reduce the percolation rate on average to 5-10% of precipitation once vegetation has been established (initially grass, re-foresting in 2002/03).

a) b)

FIG.7. Beerwalde waste rock pile a) Beginning of the relocation of the Drosen dump. The material is placed on an extension area of about 10 ha which has been sealed before relocation (August 1998). b) Cover placement (October 2001).

The conical piles of Reust and Paitzdorf were scheduled to be relocated at the end of the project since they contained class C material exclusively. In June 2004 the relocation of the Reust dump was started, and it was completed in 2007. A final challenge, however, consisted in the removal of the Paitzdorf dump with a total volume of almost 8 Mm^3 to be transported over a distance of 5.5 km within a 12-month time period in 2006. In order to realize the relocation work under these time constraints additional equipment had been temporarily applied, including six CAT-777 haul trucks and eight articulated dump trucks Volvo A-40D. The transportation road, constructed from waste rock material, had to cross a public road and a railway line. Since it mainly had to be constructed on virgin natural ground the bottom of the road had to be sealed with a layer of compacted loam in order to avoid contamination of the underground by seepage water (Figures 8 and 9).

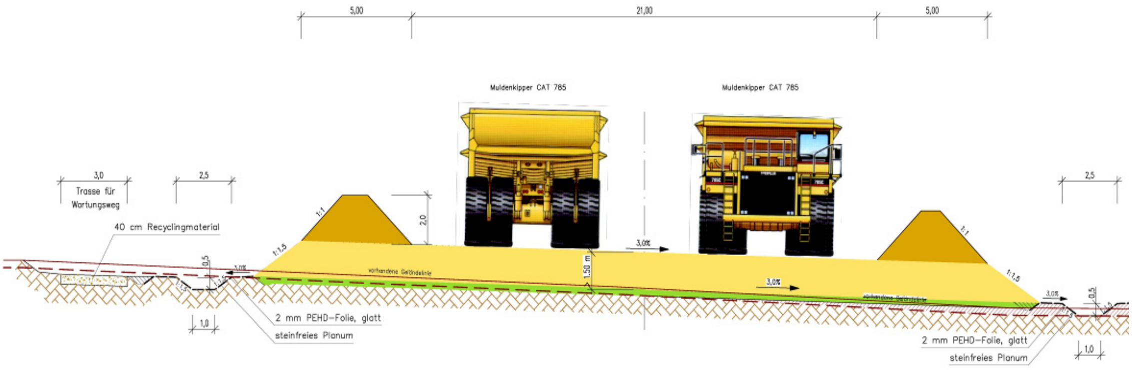

FIG.8. Cross section of the transportation road for the relocation of Halde Paitzdorf (source: IWU, 2004).

FIG.9. Construction of the transportation road from Halde Paitzdorf to the Lichtenberg open pit with waste rock. View from the dump towards the former Reust dump, which had already been relocated. June 2005.

In January 2008 the entire waste rock relocation project was finished with the conclusion of the removal of the so-called ‘Schutzdamm’, a dam like pile of 150 000 m^3 situated in the immediate vicinity to the community of Ronneburg. Its relocation had been initiated immediately after the end of the BUGA exhibition in October 2007. The total material balance of the backfill operation is outlined in Table 5.

TABLE 5. MATERIAL BALANCE OF THE BACKFILLED OPEN PIT AFTER COMPLETION OF THE WASTE ROCK RELOCATION (AS PER 31.01.2008)

Zone	Material deposited (Mm^3)
A	50.0
B	50.8
C	30.8
Total	131.6

To run the entire project 204 individual permits had to be applied for. All measures relating to final contouring, cover construction, re-vegetation, and dewatering/flood protection have been concentrated in a planning approval procedure, which has not yet completely finished until now.

Construction activities for the final soil cover started in 2005 in parallel to the remaining relocation activities. By the end of 2007 117 ha of soil cover had been completed, which corresponds to about 50% of the total area of the backfill body. Within the same time span, 9 km of access roads and 8 km of dewatering ditches were realised (Figures 10 and 11).

FIG.10. Reclaimed Ronneburg mine site, with the almost completely backfilled former Lichtenberg open pit, partially covered and re-vegetated (May 2007). Footprint areas of the Nordhalde (foreground, re-vegetated), Absetzerhalde (right), and Halde Reust (background).

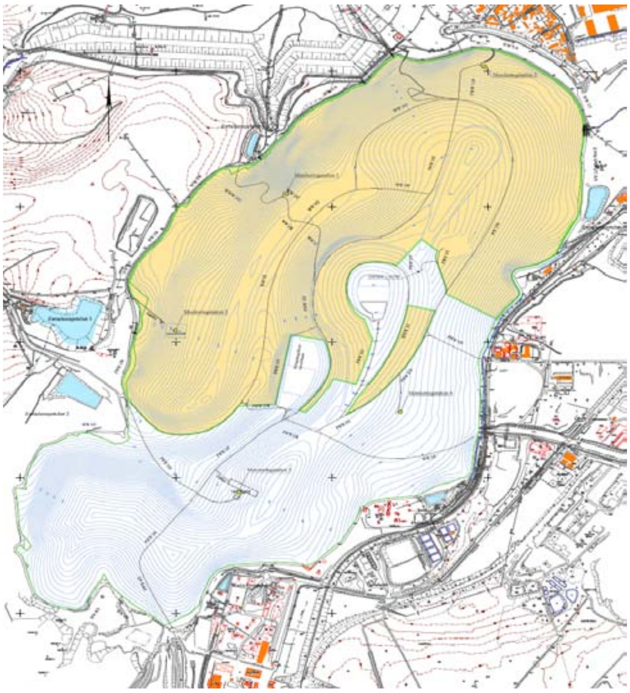

FIG.11. Final contour of the Lichtenberg Backfill after complete waste rock relocation. Areas already covered are highlighted in brown (per 31.01.2008).

The remaining activities, which will be presumably finished by the end of 2010, are comprising the completion of the soil cover including re-vegetation measures, the construction of another 8 km of access roads and 12 km of dewatering facilities, and finally the construction of a stormwater storage reservoir of 141 000 m^3 capacity for flood protection of the downstream riparian community of Ronneburg.

After 17 years of remediation activities the reclaimed Ronneburg mine site is now offering a multitude of possibilities for a prosperous regional development, as it has been demonstrated by the Federal Horticultural Show BUGA 2007, which had been partially implemented across reclaimed former mining areas, in the immediate vicinity of the former Lichtenberg open pit mine.

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REMEDIATION OF THE RADIOACTIVE TAILINGS PONDS IN THE NAVOI MINING AND METALLURGY COMBINE (NMMC), UZBEKISTAN

V. A. Grutsinov
Navoi Mining and Metallurgy Combine, Navoi, Uzbekistan

Invited paper by UMREG for the IAEA

Abstract

During 1964 to 1995, all uranium ore mined in Uzbekistan was processed at the Navoi Hydro-Metallurgical Plant producing 57 059 270 tons (solid mass) of uranium tailings, deposited in an impoundment extending over more than 637 ha, which is subdivided into 8 compartments. After 1996 the processing at the Navoi plant switched to processing of gold ore. To handle the legacy of the uranium ore processing a remediation project was implemented, which consists of hydraulic placement of thin layers of gold tailings over the uranium tailings up to a thickness necessary to reach the required attenuation of gamma radiation, radon exhalation and infiltration of precipitation. By gradual placement of thin layers and following a successive loading-consolidation and reloading cycles the covering of weak, compressible tailings becomes possible. The placement of tailings cover layers alternates between the tailings compartments, thus allowing the drying/consolidation in one compartment while continuing the cover placement in the next compartment. After construction of the attenuation layer, a layer of fertile soil is placed to support vegetation of the final surface and protect the remediated tailings from erosion. The implemented remedial solution provides the necessary confinement of the uranium tailings and has a better economic performance than the dry cover placement.

INTRODUCTION

All uranium ores mined from the sandstone type deposits of Central Kyzylkum (Navoi and Samarkand Regions of Uzbekistan) during 1964-1995 were processed at the Navoi Hydro-Metallurgical Plant #1 (HMP-1). The hydrometallurgical extraction of uranium from the ore was by sorption leaching and extractive concentration technology producing U_3O_8 as the final product. The radioactive wastes of the processing, i.e. the tailings mixed with water (pulp), were being delivered through a pulp-line to the tailing ponds located within 5 km of the plant.

In 1995, as a result of the introduction of a new mining technology, the In Situ Leaching of uranium ore deposits through injection and extraction wells, all conventional uranium mines (open pits and underground mines with shafts) were closed. After closure of the mines there was no need for discharge of radioactive pulp into the tailing ponds anymore. Instead, the question arose, "What should we do with the radioactive tailings from the former activity?"

Due to the fact that the conventional remediation method (i.e. delivering the earth materials to the tailings beaches by trucks and using bulldozers to spread the material over the tailings surface) was too expensive for NMMC and due to the intent to continue employing the redundant workers at NMMC, a series of special tests have been initiated to find a different method suitable for uranium tailings remediation.

Upon closure of the uranium processing line at Navoi, the specialists of the company decided to use HMP-1 for processing gold ore from the Marinate Open Pit Mine located approximately 200 km to the north of Navoi and to use the non radioactive wastes of gold processing as material for building a radiation attenuation layer above the radioactive uranium tailings from the former activities of the plant.

To this end the Uzbek Geotechnology Design Institute in Tashkent developed the "Project of Ecological Rehabilitation of the Tailing Ponds of HMP-1" using gold processing wastes, which started being implemented immediately after the approval of the Central Ecological Expert Commission of the Republic of Uzbekistan (NMMC) has been received.

The multi-compartment tailings impoundment of the uranium tailings at navoi

The storage facility of the tailings from the uranium processing is a flat impoundment with walls of 5 to15 m high. The tailing impoundment has an area of 637 095 ha and is divided into 8 compartments (collectors), to which the pulp was being delivered alternatively.

Approximately 57 059 270 tonnes (solid mass) of pulp accumulated in the tailing impoundment during the operation of the uranium processing plant (1964 to 1995). The thickness of the radioactive tailings in the compartments varies from 2 to 15 meters.

The specific alpha activity of the tailings varies from 10 to 110 kBq/kg, with an average value of 90 kBq/kg. The total radioactivity of the accumulated wastes was appraised to be 145 thousand curie. During an inspection survey of the tailings, impoundments by means of SRP-68 instrument a 500-1700 µR/h dose rate measured 10 cm above the tailing pond in the central zone of the compartment. The average density of radon exhalation from the tailing ponds surface was 4.1 Bq/m^2 sec.

Characterization of the gold processing tailings

The annual output of the gold processing plant is 700 to 750 thousand tons of gold tailings which is delivered to the tailings impoundment and spread on the surface of the uranium tailings as a radiation attenuation layer.

The typical characteristics of the gold tailings pulp are as follows:

- Consistency indicated by the solid to liquid ratio,
  - S:L= 1 : 2.12.
- Gold tailings grain-size distribution in weight %,
  - 0.4 – 0.16 mm–1.4
  - 0.16 – 0.074 mm–14.7
  - 0.074 mm– 83.9
- Chemical composition of the solid phase of the pulp (weight %):
  - Silicon oxide – 70.4; iron oxide – 5.6; calcium oxide – 1.7;
  - Magnesium oxide – 1.8; aluminum oxide – 12.0; manganese oxide – 0.07;
  - Titanium oxide – 0.53; sulfur total – 0.75;
  - Potassium and sodium oxide – 6.41;
  - Others – 0.74.

The only hazardous component in the gold pulp, which remains after waste neutralization in the plant, is a content of 1 to 2mg/l of cyanides in the liquid phase. Under the arid climatic conditions of the site the cyanides present in the liquid phase get completely decomposed during the evaporation period due to exposure to the solar radiation.

The solid phase of the pulp, i.e. the tailings have in average a specific weight of 1.4 g/cm^3 and a moisture content of 19–20%.

The natural specific total alpha activity of the gold bearing ore varies from 700 to 1000 Bq/kg.

The basic technical objectives and specific remedial measures implemented within the project

The construction of a radiation attenuation layer by hydraulically covering the surface of the radioactive tailings with the non radioactive gold tailings should ensure the reduction of the:

(1) Gamma-radiation from the uranium tailings to 100 μR/h;
(2) Radon exhalation from the same tailings below the recommended limit of an effective individual dose of 1 mSv per annum;
(3) Infiltration of precipitation to the uranium tailings, thus decreasing the leaching of these tailings and the impact on the ground water below the tailings impoundment.
(4) The estimation of the "necessary" thickness of the gold tailings cover over the uranium tailings was based on these specifications.

The technical measures used for implementation were as follows:

1. Layers of radioactive pulp are placed (washed in) hydraulically up to the total thickness required to attenuate the gamma-radiation dose rate initially measured on the surface of the uranium tailings (Figure 1). The required thickness of the radiation attenuation cover was usually between 0.7–1.5 m.
2. The final thickness of the uranium tailings cover is built up gradually by successive placement of pulp layers of 15–20 cm thickness. After having completed the placement of a thin layer in one compartment, the layer placed was left to dry and the discharge of the pulp continued in another compartment, which was already dry. The cover placement procedure was continued there. The placement of the next thin layer continued after the previously placed thin layer became dry. Geomechanically, the important effect of the "drying" phase is that sufficient time is provided for the placed layer to both consolidate and exercise an increasing load on the tailings underneath. The reason for placement of thin layers is to cut down the time needed for consolidation. Due to the drying, however, a contraction of the thin layer in the range of 13–15% occurs, which results in fissures. Thus, one of the additional functions of the next upper layer becomes to fill in the desiccation fissures. The gradual placement of thin layers with successive loading-consolidation and reloading cycles is a well proven method for stabilization of extremely weak and compressible tailings irrespective of the type of placement (hydraulic or mechanical) of the cover.[1]
3. Under the arid climatic conditions at the site of the Navoi tailings impoundment the "resting" time needed for the hydraulic fill layer in a tailings compartment -during which the thin layer consolidates and acts as a load- is between 15–20 days.
4. The overall cover of the uranium tailings is built as a two-bed (duplex) system. The lower bed placed directly on the uranium tailings serves as the layer controlling the gamma radiation, radon exhalation and infiltration of the precipitation into the tailings. The upper bed is designed to protect the tailings surface against wind erosion and support the

[1] The advantages of successive placement of thin cover layers on unconsolidated tailings is discussed in: Wels, C., A. MacG. Robertson and A.T. Jakubick," A Review of Dry Cover Placement on Extremely Weak, Compressible Tailings", Sudbury '99, Mining and the Environment II, Sudbury, September 11-12, 1999, CIM Bulletin, Volume 93, No. 1043, Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, September 2000

vegetation of the surface. The thickness of the upper bed is 0.3 m and is made of potentially fertile soil. The upper bed is placed on the radiation attenuation bed mechanically.

Owing to the high density of the gold tailings, its grain-size distribution and method of hydraulic placement, the effectiveness of the uranium tailings cover of 1m thickness provides an effect equivalent to a 2.5 m thick soil cover.

FIG.1. Discharging the tailings from gold processing over the "old" uranium tailings into the tailings impoundment at Navoi, Uzbekistan.

Machinery used for implementation

The first radiation attenuation layer was built by the same equipment which was used for the wastes disposal: the main discharge pipe, distribution pipelines and mud pumps. The second protecting layer was formed as follows: excavation of the soil, transportation by trucks to the impoundment and spreading of the soil uniformly to build a 0.3 m layer on the surface of the previously constructed first cover.

The extent of work completion

So far more than 7 million tons of gold processing tailings have been placed to build a radiation attenuation cover above the uranium tailings of the former processing plant. The tailing compartment:

- №5 (100 hectares) has been covered in average by a 1.5 m thick cover;
- № 6 (80 hectares) has received a cover of 3.5 m average thickness; and
- № 3 (110 hectares) is covered by a layer of 0.5 m average thickness.

Currently, remedial works is ongoing on ponds № 4 and № 7 and pond № 8 has been prepared for remediation.

For construction of the radiation attenuation cover of the designed thickness over the whole tailings area, approximately 13–15 million tons of gold processing wastes will be required and for the protection cover approximately 2 million m^3 of the potentially fertile soil will be needed.

Costs of the completed works

The first project for remediation of the uranium tailings of HMP-1 was developed by the All-Russian Design Institute for Industrial Technology (VNIPI) in 1994. The projected design proposed a three-layer cover system that would be laid mechanically over the whole surface of the dry tailings. The costs of this tailings remediation project were estimated to amount to 135 million USD.

The costs of the adopted project for construction of the attenuation layer using the hydraulic placement of the presently generated gold tailings over the uranium tailings are compensated by the gains from processing of the delivered ore and production of gold at the Navoi processing plant (NMMC).

PHASED REMEDIATION APPROACH FOR PREVENTION OF RISKS LINKED WITH URANIUM TAILINGS IN MAILUU-SUU, KYRGYZSTAN

H. Vandenhove[1], J.J. Clerc[2], H. Quarch[3], A. Aitkulov[4], M. Savosin[5], I. Torgoev[6], M. Mirzachev[7]

[1]Belgian Nuclear Research Centre
[2]GESTER, Techniparc, Nanterre, France
[3]Gersheim, Germany
[4]Assay and Environmental Laboratories, Kara-Balta, Kyrgyzstan
[5]CHU-Ecological Laboratory, Kara Balta, Kyrgyzstan
[6]Geopribor, Bishkek, Kyrgyzstan
[7]KyrgyzGIIS, Osh, Kyrgyzstan

Invited paper by UMREG for the IAEA

Abstract

The area of the town of Mailuu-Suu, Kyrgyzstan, is polluted by radionuclides and heavy metals from tailing dumps and heaps resulting from the historic exploitation of uranium mines. In the frame of a European Commission-TACIS funded project, we evaluated measures to be taken by the authorities to reduce the radiological exposure of the population and to prevent environmental pollution by radionuclides and heavy metals in case of loss of tightness of dams and damage to dumps and heaps from mining and milling by land and mudslides and proposed sustainable remedial options, accepted by the public.

A radiological assessment was performed for critical group members living in the city of Mailuu-Suu, located downstream of the tailings, or in the village of Kara Agach, partially located on a uranium mine-waste dump. The actual external exposure is around 1.2 mSv a^{-1} at both locations and exposure from radon is around 3 mSv a^{-1} at Mailuu-Suu and around 10 mSv a^{-1} at Kara Agach. Ingestion dose was negligible for a critical group member living at Mailuu-Suu. At Kara Agach, however, under the very conservative hypothesis that all food and fodder is cultivated locally, exposure from ingestion is much higher (~10–30 mSv a^{-1}). Additional dose from irrigation with Mailuu-Suu river water is small in actual conditions (< 0.1 mSv/year). However, there is an important possibility that triggered by an earthquake or a landslide, (part of the) tailing(s) content may be directed to the river Mailuu-Suu. Doses to the affected population may increase to multiple ten mSv per annum. Given the actual limited stability of Tailing N° 3, the potential of such a disaster to occur is non-negligible. To impede the consequences of a potential disaster, under the TACIS project different remedial options are evaluated for Tailing 3 including in situ stabilization and tailing translocation. Also more global remedial options for the Mailuu-Suu River valley are studied (translocation of other tailings, tunnel to deviate river, partial protection of river from landslide blockage). It was proposed to acquire a phased approach in time performing urgent limited stabilization options for Tailing N° 3, improve the stability of the Tailing N° 3 by COLMIX-columns in the medium-term, while investigating and evaluating further two long term remedial options: the translocation of the tailings and the long-right-bank river diversion tunnel.

INTRODUCTION

The area of the town of Mailuu-Suu, Kyrgyzstan, is polluted by radionuclides and heavy metals in tailing dumps and heaps resulting from the historic exploitation of U-mines in the Mailuu-Suu area in Kyrgyzstan. Radioactive substances are stored in 23 tailings and 13 mining debris heaps situated along the Mailuu-Suu River (Figure 1). The stability of many tailings is at risk. Some of those tailings are already damaged by landslides, mudslides and floods, and some others are in high-risk areas where major landslides are expected. High risk for potential future exposure is present at deposits located along the riverbank in the narrow gap of the Mailuu-Suu River immediately south of the village of Kara Agach. Tailing N° 3 is considered as being the more risky one, because of its important radionuclide inventory and since it is threatened by a major landslide.

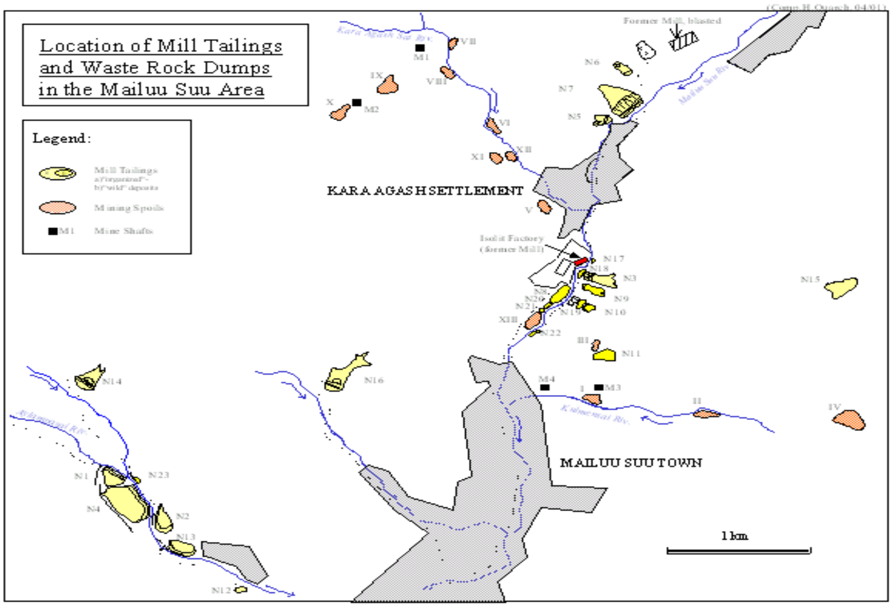

FIG.1. Location of mill tailings and waste rock dumps in the Mailuu-Suu area, Kyrgyzstan.

Major landslides potentially affecting directly or indirectly uranium ore processing tailings deposited along the Mailuu-Suu River valley (i.e. tailings deposits N° 3, 9, 10, 8, 5 and 7 are the Tectonic, Technicum, Isolit and Koetash landslides which have already partially caused river blockages in previous times (such as Tectonic Landslide in 1992). Earthquakes may have a direct or indirect effect on mudflows or landslides. Kyrgyzstan has been affected by a series of seismic disasters, the strongest being the Ms=8.2 Kemin earthquake in 1911. Recently, the Ms=7.3 Suusamyr earthquake affected the Northern and central Tien Shan mountain regions.

The objective of the EC-TACIS funded project is to evaluate measures to be taken by the authorities to reduce the radiological exposure of the population and to prevent environmental pollution by radionuclides and heavy metals in case of loss of tightness of dams and damage to dumps and heaps from mining and milling by land and mudslides and to propose sustainable remedial options. The specific project objectives were (1) to identify the risks (radiological and others), (2) to propose measures to monitor and to mitigate those risks, (3) to study and evaluate rehabilitation plans for Tailing 3 and evaluate how the approach for Tailing N° 3 can be applied to other tailings, (4) to implement short-term remedial measures on Tailing N° 3, (5) to study and evaluate rehabilitation plans to decrease the impact of a disaster scenario.

The outputs/sustainable results are (1) the improvement of knowledge on risk situation at Mailuu-Suu, (2) the improvement of the situation at Tailing N° 3, (3) improved environmental protection (4) improved monitoring and prevention systems, (5) a feasibility study for a number of remedial options which can be used as a basis for decision taking, (6) improved information and awareness of the population. This paper highlights some aspects of the final report of the EC-TACIS Project N° SCRE1/N°38. [1]

RESULTS AND DISCUSSION

Results of the radiological monitoring campaign

The monitoring campaign

In August 2001, tailings were screened for external gamma exposure in order to indicate areas of concern and set up a priority list of tailings to be fenced. A gamma monitoring network was set up comprising 65 measurement points (tailings, rock piles, in Kara Agach and Mailuu-Suu (for both outside and in houses). Radon monitoring was performed during one year (two six-monthly measurements) on 50 different locations in Mailuu-Suu.

Borehole samples were taken at Tailing N° 3, 5, 7, 8 and 15. Samples were analysed for physical parameters for determining tailing stability. Samples were also analysed for U, total alpha, radium, Th, Pb, some heavy metals for assessing the contaminant content and also gamma rate was measured. Samples were further analysed for dispersion relevant parameters. The results for the tailing boreholes are used for the calculations of the leaching from Tailing N°3 and assessment of potential radiological consequences in case of disaster.

Soil samples were taken at locations with elevated gamma radiation at the tailing surface or at the village of Kara Agach. As a rule vegetation samples were taken at the place of the soil samples. Sediment samples and water samples were taken at different locations along the river Mailuu-Suu: from the water treatment plant, upstream all tailings, to the entrance of the town Mailuu-Suu. Food and drinking water was collected.

All data on gamma exposure, radon exposure, activity levels in soil, water, vegetation, food etc are used for the radiological dose calculations.

The major findings from the radiological monitoring campaign

From the gamma radiation monitoring campaign, it showed that the background radiation is 100–120 nSv/h. The average outside and in-house radon concentration is 175 Bq/m³. In three of the houses monitored at Kara Agach the radon level is between the EU-exemption limit for new (200 Bq/m³) and old (400 Bq/m³) houses. The actual gamma and radon values recorded are not exceptional for uranium mining area. External radiation and radon levels are normal for uranium mining areas. Additional external exposure above background is smaller than 0.4 mSv/a. The radon level in one house in Kara Agach is higher than the 400 Bq/m³ action level for old houses. Owners should be advised to ventilate their house and radon levels should be continuously monitored if no relocation is foreseen.

The concentration of uranium in the Mailuu-Suu River water is far below the exemption limit for drinking water set in Kyrgyzstan. Water should best be filtered since the sediments contain radionuclide concentrations higher than the exemption limits for soil. The locally provided drinking water in Mailuu-Suu and surrounding villages is safe for human consumption.

Soil sampled at hot spots at tailings, surroundings of tailings and Kara Agach have radionuclide concentrations above the exemption limits. T3, T5, T7, T4 should certainly be fenced but also at other tailings trespassing by people and animals should be restricted.

At Kara Agach soil samples measured exceeded the exemption limits for uranium and radium with about a factor 20 for uranium and between 8 and ~1600 for radium. Cultivation of food crops and animal fodder should be prohibited at these locations in Kara Agach. Children should not play on these soils! At Mailuu-Suu levels in soil are a factor 20 and much more lower than at Kara Agach.

All vegetation and crops sampled on the tailings and in Kara Agach exceed the limits for alpha, uranium and radium. People living at Kara Agach should be advised not to use locally grown or reared food stuffs. Uranium concentrations in food collected at the Mailuu-Suu market place and locally grown food were below the limits.

Assessment of actual radiological exposure

The release of radionuclides from the tailings and waste rock deposits may give rise to exposure of the local population via different pathways. The exposure can take place directly via external irradiation and indirectly via inhalation of resuspended soil particles, radon, and ingestion of locally produced food products like vegetables, fruit, milk etc. For the Mailuu-Suu region, a subsistence farmer community is used as representative for the habits of the critical exposed individuals. This is based on the assumption that subsistence farmers make a (reasonable) maximum use of local environmental resources. Age-dependent variations in metabolism are considered by calculating the individual dose to an adult and a child (10 years). A habit survey was conducted to investigate the dietary characteristics of the local community and to characterise how local environmental resources are exploited. These data were used to derive the characteristics of the critical group. To assess the dose impact on individuals of the critical group, a biosphere model was used. This model describes the transport of the radionuclides released into the biosphere, their transfer through the food chain and the subsequent exposure to humans. The exposure was assessed for Mailuu-Suu and surroundings in general and for the village of Kara Agach, situated upstream of Mailuu-Suu and partially built on an ore debris waste dump.

External exposure and inhalation dose

The external exposure is around 1 mSv/a in Mailuu-Suu and Kara Agach of which 0.8 mSv/a is due to background radiation. The radon exposure is around 5 mSv/a. in Mailuu-Suu and Kara Agach. This is considered normal and is below the 7 mSv/a to which a person living in a house with 400 Bq/m³ (European action level) is exposed. If the radon concentration in the one house at Kara Agach with very high radon concentrations would be included, the radon exposure would be 10.5 mSv/a (Table 1). Dust inhalation, even from the contaminated soil at Kara Agach (at Mailuu-Suu soil contamination levels are about a factor 10-20 lower) is negligible (< 0.1 mSv/a).

TABLE 1. PREDICTIONS OF THE RADON INHALATION DOSE AND EXTERNAL DOSE OF CRITICAL GROUP MEMBERS (MSV/Y)

Place	Adult				Child (10 years)			
	Inhalation of exhaled radon		External irradiation		Inhalation of exhaled radon		External irradiation	
	indoor	outdoor	indoor	outdoor	indoor	outdoor	indoor	outdoor
Kara Agach	1.02E+01	3.01E-01	1.10E+00	1.22E-01	7.83E+00	3.78E-01	1.24E+00	2.27E-01
Mailuu Suu	4.69E+00	2.64E-01	1.04E+00	1.02E-01	3.60E+00	3.32E-01	1.18E+00	1.89E-01

Ingestion dose

Most of the dose for people living at Kara Agach comes from the ingestion of contaminated food (> 10 mSv/a). It is very conservatively hypothesised that people living at Kara Agach consume locally produced food and consume water from the Mailuu-Suu River. In fact people by in uncontaminated food and consume uncontaminated water provided by the water treatment plant. When consuming locally grown crops in Mailuu-Suu town (factor 10–20 lower soil contamination), the expected ingestion dose would be a comparable factor lower.

It is seen that the calculated doses for the current situation at Kara Agach are much higher than the dose limit of 1 mSv/y for members of the public. For an adult and child (of 10 years) of the critical group living at Kara Agach, a total dose of 22 mSv/y respectively 39 mSv/y was obtained (Table 2). The ingestion of drinking water contributes with less than 0.1 mSv/a to the total ingestion dose, the standard set by WHO.

TABLE 2. CALCULATED TOTAL DOSE (MSV/Y) FOR THE CURRENT SITUATION FOR A PERSON LIVING AT KARA AGACH

	Inhalation dose		Ingestion dose	External dose	Total dose
	dust	radon			
Adult	7.77E-02	1.05E+01	9.61E+00	1.22E+00	2.14E+01
Child (10 years)	7.72E-02	8.21E+00	2.89E+01	1.47E+00	3.86E+01

Looking at the Kara Agach situation, we see that the ingestion dose and inhalation dose of radon are the main pathways. Since more than 90% of the ingestion dose is caused by the ingestion of locally cultivated food crops, we would recommend restricted use of these food crops. The dose due to inhalation of radon in indoor air can be reduced by increasing the ventilation rate in the houses and other protective actions which limit the radon flux from soil into the houses. Another necessary action would be to move people living in the one house with high indoor radon content.

The dose limit of 1 mSv/y is however not directly applicable to cleanup decisions. ICRP 82 recommends the use of generic reference levels: 10 mSv/y is chosen as generic reference level below which intervention is unlikely to be justifiable for prolonged exposure situations. Above an existing annual dose of 100 mSv/y intervention will almost always be justified. For an existing annual dose between 10 mSv/y and 100 mSv/y as obtained for Kara Agach, ICRP states that intervention may possibly be necessary and its justification should be considered on a case-by-case basis as appropriate.

People may use the river water for irrigation practices: this is actually not the case for people living in Mailuu-Suu and villages nearby but people living downstream Mailuu-Suu do so. The extra dose from irrigation with contaminated river water is negligible < 0.1 mSv/a).

Assessment of risk

Extent of radionuclide leaching of Tailing 3

Hydraulic modelling for Tailing 3 was performed in order to estimate the direction and magnitude of water flow under saturated and unsaturated conditions without taking into account potential inflow from uphill areas. Transport calculations were done for the four species decay chain 238U => 234U => 230Th => 226Ra. The flow model assumes that groundwater velocities are vertically downward above the groundwater table, whereas below groundwater table a strong lateral component exists. At the seepage face, which is supposed to correspond with the interface with the nearby river, velocities are largest as all flow paths converge in a fairly small cross-sectional flow area.

- Considering the available data on the radioactivity inventory and some dispersion relevant parameters, and considering an average annual Mailuu-Suu river flow rate (9.1 m^3/s) the hydraulic modelling estimated following concentration load in the Mailuu-Suu River following leaching from Tailing N° 3 (Table 3).

TABLE 3. CALCULATED MAXIMUM CONCENTRATION IN MAILUU-SUU RIVER BASED ON THE FIRST 10 000 YEARS CONSIDERING A RIVER FLOW RATE OF 9.1 M^3/S

	U-238	U-234	Th-230	Ra-226	Th-232	Ra-228	Th-228
Max. concentration in river water (Bq/m^3)	2.1E-1	2.1E-1	1.0E-4	6.7E-4	2.1E-1	1.0E-4	6.7E-4
Standards in Kyrgyzstan	21800	81400	8140	1998			

It is clear that the expected additional concentrations in the river water following leaching from Tailing N° 3 are far below the Kyrgyz limits for drinking water. As a result, there is probably no adverse effect on human health. The excess dose due to leaching from Tailing N° 3 is negligible (< 1 µSv/a). Also for the heavy metals it was demonstrated that the calculated concentrations are much smaller than the guidelines values provided by the WHO or the drinking water standards given by EPA. As a result, there is probably no adverse effect on human health, based on the values found.

Transport of radionuclides by the Mailuu-Suu River in case of disaster and resulting radiation exposure

Two scenarios were evaluated. The first scenario assumes that the waste material of Tailing N° 3 will be evacuated by the river in a few days by considering a sediment load of 10 kg/m^3 water. In agreement with the first disaster scenario, the second scenario also assumes that Tailing N° 3 is suddenly poured into the river and that the suspended matter only consists of the waste material from Tailing N° 3. The only difference is that the current mean water flow and sediment load will be used to calculate the dose. According to this second scenario, it will take about two years before the waste material has been removed by the river. This scenario leads to the higher dose increment. It is assumed that the critical group will be exposed via the same exposure pathways as considered for the current situation.

Under scenario 2, the outbreak of the Tailing N° 3 content to the Mailuu-Suu River can lead to a considerable dose to the people living downstream Mailuu-Suu since they use the river water for irrigation and drinking water purposes. Most of the ingestion dose comes from the ingestion of drinking water and consumption of fish, each accounting for 10 mSv/a for adults and respectively 25 and 9.5 mSv/a for children. Ingestion of contaminated food following irrigation accounts for 0.6 mSv/a for adults and 10 mSv/a for children. If the actual drinking water provision remains unchanged and people will be forced to use the contaminated water these are the likely doses to which people will be exposed to. There are 5000 people living downstream Mailuu-Suu in Kyrgyzstan, so the collective dose resulting from 2 years exposure may be considerable.

Stability of tailings impoundment N° 3

Stability calculations (TALREN) based on laboratory tests on tailings material also demonstrate that the current situation is apparently at the state of limited stability. From the laboratory tests, a safety coefficient of the current situation of F = 0,96 was deduced. The current situation is apparently at least at the state of limited stability, which is confirmed by the extensiometric measures undertaken by Geopribor; hence, we admit that, as a reference only, the actual safety coefficient is F = 1,00 which corresponds to the limit of equilibrium. This value of F=1.00 was used in each of the following case studies as reference.

Taking into account the seismicity of the region the influence of accelerations induced horizontally and vertically by an earthquake inside the tailing was examined. Under pressure of an earthquake applying a pseudostatic acceleration (PSA) horizontal of gh = 0.1 g (limit between 7 and 8 MSK) and a pseudostatic acceleration (PSA) vertical of gv = + or – 0,05g, the safety coefficient F is 0,71. Under the influence of a strong earthquake applying a pseudostatic horizontal acceleration of gh = 0,2 g (limit between 8 and 9 MSK) and a pseudostatic vertical acceleration of gv = + or – 0,1 g, the safety coefficient F falls down to 0,54. The Mailuu-Suu area belongs to the Central Fergana Range with an active Arslanbob fault. The associated peak ground accelerations are for this area 0.25g to 0.30g.

Remediation options investigated

In situ stabilization of Tailing 3

Stability calculations for various options using the TALREN-programme led to the conclusion that the actual stability of the tailings pond is low. Overloads or surcharges (additional material induced by hill erosion or landslides) accumulating on the top platform towards the cliff have a limited unfavourable effect. However, when additional deposition occurs close to the existing small (secondary) dam, the stability of the Tailing 3 is jeopardised.

These calculations demonstrate that the transfer of sediment load (and of the secondary dam) from this (central) area about 30m further uphill to the East has a positive (stabilizing) effect. The new dam (2m high) will stop the erosion deposits originating from the slope above and an additional gutter along the dam will redirect the runoff waters towards the concrete gutter located at the south-west angle. A cover will limit water infiltration. Also an additional embankment (cover or infill) located on the lower part of the downhill embankment of the tailing would have an extremely positive effect according to the calculations. On the other hand, an additional infill located on the upper part of the downhill embankment would have an extremely negative effect. A total cover should therefore not be applied on the entire downhill embankment but only on the bottom.

Very short term remedial measures

Accordingly reshaping and covering of the impoundment was therefore proposed in the short term. These works could be rapidly executed using the logistics available regionally.

At the end of these first works, after erosion or the landslides have added an extra layer above the embankment, the safety coefficient F becomes, for a 15 meter wide bottom embankment:

- In the absence of an earthquake: F=1.33

- During an earthquake creating PSA horizontal (pseudostatic horizontal acceleration) gH = 0.1 g and PSA vertical gV=0.05g : F=0.87
- During an earthquake creating PSA horizontal gH=0.2g and PSA vertical gV=0.1g : F=0.63

Mid term remedial measures

Hence, it was concludes that in the mid term an additional stabilization is necessary for important earthquakes. The creation of reinforcements using COLMIX columns (incorporation of cement and lime by mixing using a triple bore) strengthened by metallic girders will considerably help increase the stability (Figure 2). The safety coefficient in relation to a triple column density of 1 for 7m², strengthened by 3 steel sections HEB 200, becomes for a 15 meter wide bottom embankment:

- In the absence of an earthquake: F=1.48
- During the earthquake's PSA acceleration gH = 0.1g and gV = 0.05g : F = 0,96
- During the earthquake's PSA acceleration gH = 0.2g and gV = 0.1g : F = 0,67

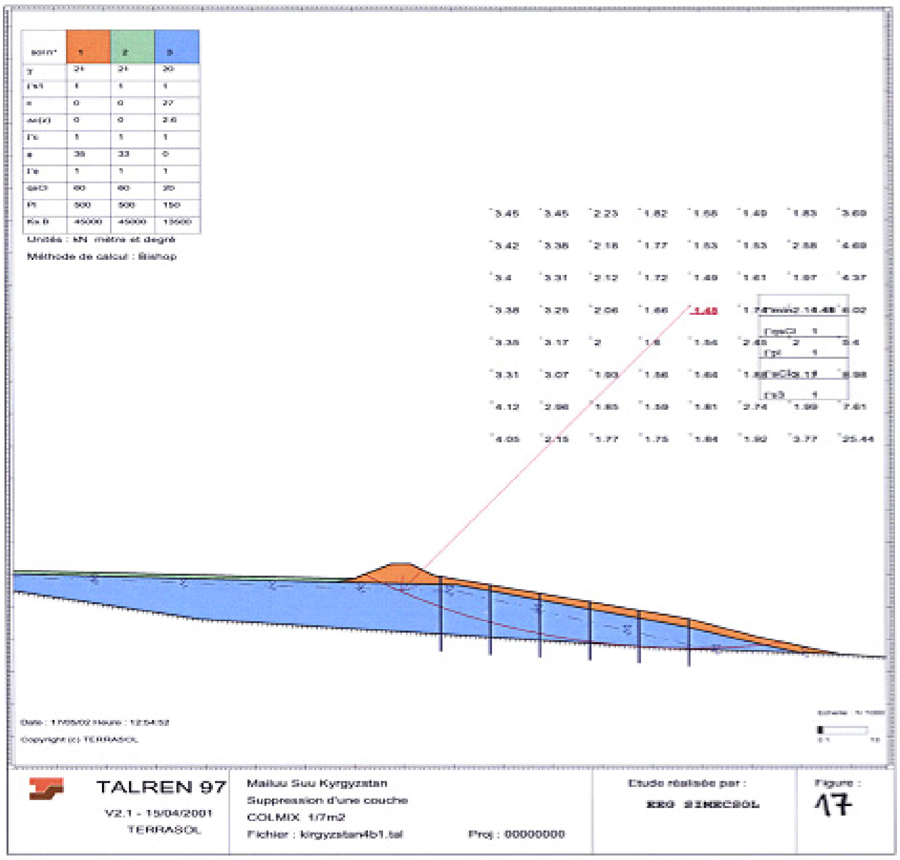

FIG.2. Safety coefficient for Tailing 3 if COLMIX with a triple column per 7 m²: F=1.48.

It is thus assessed that with one triple column per 10 m², an earthquake of a pseudostatic horizontal acceleration of 0.1 g will not jeopardize tailing stability. The expected cost of the COLMIX method was estimated at approximately 2 Mio Euro. All costs were estimated from prices before taxes applied in 2002 in Western countries, by companies working according to western standards and using suitable materials. Cost for dealing with radiation protection and control issues during the works is estimated at an additional 0.2 Mio Euro. Hydraulic modelling for T3 suggested no significant decreased leaching from T3 to the Mailuu-Suu River following application of COLMIX columns. The annual dose impact to workers when applying the COLMIX stabilization method is lower than the annual dose limits of 50mSv/y for workers and also lower than the weekly allowed doses of 1 mSv (Table 4).

Transfer of tailings to a safer site

It is understood that an earthquake has a direct adverse effect on tailing stability. Even the COLMIX improved tailings will fail in case of earthquakes with moderately high activity. The second possible adverse effect is that of a landslide or of soil creep accumulations from the escarpment cliffs east and above T3, which would create an overload or surcharge on the tailing and could provoke dam rupture. A concomitant effect is the risk of a liquefaction of the residues which are water-saturated, due to constant water influx or infiltration.

Therefore, and for the long term the alternative option of transferring T3 and other tailings depositories to a safer site has to be discussed and was investigated further.

It must be understood that the complexity of a tailings transfer with all the long term warranties, or the difficulty in extracting the radioactive residues most probably in form of a paste or mud ("pulpa") should not be underestimated. Transport conditions around the northern city limits of Mailuu-Suu must be adapted to this task, be safe enough and include appropriate measures for (radio)-protection of the population and workforce. Water treatment capacity must be installed and operate for several years. The selected alternative site must be thoroughly investigated and prepared and constructed along the guidelines of a disposal cell concept.

Hence, such relocation can not be accomplished before several years, since detailed pilot studies of the new tailings disposal site and a full fledged feasibility study still have to be prepared. Moreover it has to be realised that on top of providing appropriate transport conditions and important investment funds, adequate technologies, machinery, materials and personnel are still not yet fully available in Kyrgyzstan. Under these circumstances it is important to start with the necessary short term stabilization measures immediately or as soon as possible regardless of the outcome of the feasibility study and the final decision.

After pre-screening several sites proposed by Kyrgyzstan authorities, the location of Tailing 15 was selected for preliminary investigations including drilling a number of boreholes and examining the borehole samples. The advantages of this site are that transport does not pass through the city of Mailuu-Suu or through other populated areas and that the site has sufficient capacity to store Tailing 3 plus additional residues. The disadvantage is access to Tailing 15: the road must be improved if not reconstructed entirely. It was decided jointly with Kyrgyzstan authorities that if waste from Tailing 3 is to be transferred, the new depository will be built alongside Tailing 15.

Costs were estimated at about 3 million Euro for the transfer of Tailing 3 (80 000 m^3) and 23 million Euro for the transfer of tailings T3, T5, T7 and T8 (880 000 m^3). Costs for radiological monitoring and radiation protection during the transfer of Tailing N°3 works are estimated at 0.35 Mio Euro. Costs for continued monitoring after transfer of the Tailing are roughly estimated at 0.02 Mio Euro/year.

Workforce exposure during transport of Tailing N°3

For the discussion of the dose impact to workers, Western working conditions were considered. It is assumed that the relocation of Tailing N°3 and the construction of the new disposal site at T15 will take 18 months of work. Annual doses are lower than the annual dose limits of 50mSv/y for workers and with exception of the loading of the containers, they are also lower than the weekly allowed doses of 1mSv (Kyrgyz Norms, Mr. Mombetov, personal communications) (Table 4).

TABLE 4. INDIVIDUAL DOSE TO THE WORKERS

	Total work hours	Dose (mSv)				Annual dose (mSv/y)	Dose per week (mSv/week)
		External dose	Inhalation dose dust	Inhalation dose radon	Total dose		
Translocation of tailing 3							
Loading of containers	3520	6.16E+01	1.98E+01	1.04E+01	9.18E+01	4.59E+01	1.17E+00
Transportation of material	1170	2.05E+01	6.05E+00	3.38E+00	2.99E+01	1.50E+01	7.67E-01
Creation of new disposal site	3520	5.45E+01	1.61E+01	8.94E+00	7.95E+01	3.97E+01	1.02E+00
Treatment with COLMIX							
Stabilisation and covering	1360	2.17E+01	6.39E+00	3.34E+00	3.13E+01	1.58E+01	4.66E-01

Landslide stabilization

Transfer of the tailings does not solve fully the Mailuu-Suu public safety issue due to river blockages caused by the unloading of landslides or unstable slopes and related inundation in a catastrophic scenario. Therefore the option of landslide stabilization has to be considered among other options.

In a recent World Bank experts report [2] several suggestions have been made to try to stabilize the critical slope areas menacing the tailings depositories either directly or indirectly in the Mailuu-Suu river valley. The preliminary cost estimate of the World Bank for landslide stabilization for Koetash and Tectonic Landslides including limited tailings remediation works amounts 24.4 Mio USD. These suggestions have been examined and assessed as outlined below.

The consortium considers that the classical landslide stabilization solutions suggested by the World Bank will not be successful to stabilise the Tectonic and Koetash landslides in static and earthquake loading conditions. The technical feasibility of these actions is doubtful within a competitive budget. The consortium considers as well that the Isolit landslide cannot be stabilised economically. It is therefore proposed to find a solution to avoid the river blockage following a major landslide.

Solutions to avoid river blockage (Mailuu-Suu River diversion tunnel or river-channelling)

These options and their variants attempt the complete isolation of the tailings from the major transport vector which is the Mailuu-Suu River realizing that the landslides, independently of the presence of the tailings, are a real hazard for the Mailuu-Suu town public safety.

A summary of the remedial solutions to avoid river blockage by projecting a Mailuu-Suu River diversion tunnel or a river channelling is given in Table 5. A solution may consist in channelling the river (even at maximum flow) through pre-cast concrete tubes or through covered concrete channels which would be able to support the eventually accumulating sliding masses above and keep the river in free flow. It follows from Table 4 that solution D (channelling the river) offers the lowest cost. Unfortunately the feasibility of the solution is not proven (excavation of very stony and wide river bed of a torrent) and the risk of landslide reactivation during the operation is a real hazard.

TABLE 5. REMEDIAL OPTIONS PROPOSED TO AVOID RIVER BLOCKAGE

Sdution	Cost Mio US$	Main Comments
A. Long diversion tunnel LB	~29	• Should be combined to channelling of Kara Agach river to fully achieve the public safety objective (~5Mio US$ included in the cost estimate). Some risk of reactivation of Tectonic landslide during this sequence of the works. • Location of main fault and potential fault displacements (if active) to be clarified • Location of mining galleries and shafts to be clarified
B. Long diversion tunnel RB	~28	• Fully achieve the objective in terms of public safety • Location of main fault and potential fault displacements (if active) to be clarified • Location of Mining galleries and shafts to be clarified
C. Short diversion tunnels RB		• Due to the constraints for locating the portals, the tunnels cannot be short (unless T5 and T7 are relocated). Final solution equivalent to the long RB tunnel (Solution D).
D. Channelling the river	~22	• The necessary excavations could reactivate Koetash and Tectonic landslides during the works. Risk extremely difficult to evaluate. This makes the feasibility of the solution questionable.

The long diversion tunnel solutions (Solutions A and B) do achieve the public safety objective of decreasing almost fully the dispersion of radionuclides and heavy metals by the water flow. Solution A (Left Bank) is slightly more expensive and presents some risks of landslide reactivation[1] when installing concrete elements to channel Kara Agach river (another potential contaminant transporter) flow in front of Tectonic Landslide. Therefore the best solution as considered by GESTER at the present state of knowledge appears to be solution B, the long diversion tunnel in the Right Bank which allows coping easily with the Kara Agach River.

GESTER believes that the crossing of active faults by the proposed tunnel (solutions A and B) does not impede the feasibility of the tunnel solution. Should there be evidence of recent activity of the Mailuu-Suu fault, then engineering solutions could be designed to cross the fault. These solutions can be the combination of a larger chamber (say 8m diameter supported with flexible rock support solution) with the main river tunnel crossing the fault on a bridge inside the chamber. The tunnel in these critical sections could be a steel articulated penstock. The budget given in the present report allows coping with this type of situation along a few decametres. Local tunnel design adaptations will also be necessary if the tunnel crosses the area of underground mine workings. Due to these and the geological features, the tunnel should be excavated with classical drill and blast technique (and not with a full face tunnelling machine).

In this assessment costs estimated by GESTER for the tunnel construction (without landslides hazard mitigation and limited tailings remediation work) are close to 28 Mio Euro. These costs include design, construction (Mailuu-Suu River diversion) and supervision (periodic inspections and fulfilment of public safety objectives).

[1] Risks are not as important as with solution D (reduced width of the concrete elements and necessary excavations).

It should be mentioned that resolving the problem of a possible river obstruction will not fully solve the problem for the people at Mailuu-Suu, for instance the impact of a landslide or an earthquake and part of Tailing 3 is taken to the original Mailuu-Suu River valley, people living nearby may be exposed to the tailing material by increased inhalation dose from contaminated dust and radon.

Proposed option: phased approach considering a combination of techniques

As outlined above, potential impact or indirect effect on some of the radioactive waste depositories deposits in the Mailuu-Suu river valley (namely of Tailings 3, 5, 7, 8, 9, 10, 18, 19, 20 and 21) by seismic and/or slope- or structural instability – risks cannot be excluded. Historically this has been the case for tailings depository No. 17 which was impacted by a Tectonic Landslide in 1992. For this reason remediation options have to be selected that address the so-called accidental or catastrophic scenario as a non-negligible probability of occurrence.

Seismic hazards triggering slope instability and potentially loss of structural stability of waste deposits and associated repetition of river blockage events have to be classified as likely in the mid term and long-term based on historical and even recent observations. Very little can be done against slope movement and seismicity in the critical sections of the Mailuu-Suu river valley.

Therefore access restrictions, monitoring, emergency preparedness measures and structural or physical stabilization of impoundments that have to be considered as unstable in their present condition (i.e. Tailing N°3), can only have short to mid term significance but are nonetheless necessary.

Under the present project, given the project objectives, the Consortium focussed its attention on Tailing pond N°3.

In the very short-term it is proposed to proceed with the fencing of the tailings of concern (Tailings N°3, 5, 4, 7 and 13), put on warning signs on all other tailings awaiting fencing, and perform the minimal maintenance work (repair and cleaning of gutters, damaged dams, etc.) and monitoring. Additionally to execute fully the short term stabilization works on Tailing N°3 (Reinforcement of foot of tailing and displacement of upper dike with 20 m with a resulting increased stability of 30%). Even if those short-term remedial options would not guarantee tailing stability following an earthquake of moderate intensity, they were proposed given the actual limited stability of the tailing.

Since an additional stabilization is necessary for important earthquakes, it is proposed to stabilisze Tailing N°3 downhill embankment using COLMIX treated columns in the short-mid term. It can be decided by the responsible authorities that these stabilizations are sufficient for the reasonable foreseeable impediments. Under consideration, due to extreme caution that catastrophic conditions could bring down (part of) Tailing N°3 to the Mailuu-Suu River, it may be decided to relocate the tailing. Such a translocation cannot be accomplished before several years since detailed pilot studies of the new tailing still have to be prepared. On top of that there are, the transport conditions, the important investment funds, the meeting regarding available material, equipment and personnel which are still not fully available in Kyrgyzstan. It then becomes important to start the first stabilization measures presented as soon as possible.

For all the other tailings the actual stability should be investigated, possibly following the method applied for Tailing N°3. It should be decided if the actual stability is adequate or if it should be improved and if the improved stability is acceptable.

For the long term, and following the evaluation of a number of remedial options, two options are retained:

— Excavation and transfer (first of T3 (80 000) then, T5, T7 and T8 (800 000 m^3) to an alternative safer site which could be Tailings depository No. 15 pending more detailed investigations which are necessary and beyond the scope of the TACIS project.
— Diversion of the Mailuu-Suu river by the long diversion tunnel in the right Mailuu-Suu River Bank which allows also to cope easily with the Kara Agach River.

Both options were only outlined to some extent within the framework of this project and require an even more detailed site investigation, detailed feasibility study and project design before a final decision can be formulated. Options should be evaluated in terms of technical feasibility, health and environmental impact, economic costs and public acceptance until a decision can be made to choose between the two alternatives which will be projected subsequently.

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ENVIRONMENTAL IMPACT AND REMEDIATION OF URANIUM TAILINGS AND WASTE ROCK DUMPS AT MAILUU-SUU (KYRGYZSTAN)*

C. Kunze[1], U. Walter[1], F. Wagner[1], P. Schmidt[2], U. Barnekow[2], A. Gruber[3]
[1]WISUTEC Wismut Umwelttechnik GmbH, Chemnitz, Germany
[2]Wismut GmbH, Chemnitz, Germany
[3]Geoconsult ZT GmbH, Salzburg, Austria

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Abstract

This paper describes the environmental situation in the former uranium mining and milling region of Mailuu-Suu (Kyrgyzstan), the approach to environmental remediation of the waste facilities (tailings ponds and waste dumps) and the results achieved so far. It starts with an outline of the history of the environmental remediation project which has received international attention and is seen as a pilot project for further remediation activities of former uranium mining and milling sites in the region. Apart from technical aspects, the paper draws conclusions with respect to the administrative environment, institutional capacity building and the local availability of resources needed to successfully implement a complex remediation project.

INTRODUCTION

The town of Mailuu-Suu is located in the north-eastern part of the Fergana valley, in the valley of the Mailuu-Suu River. The altitude of the area is between 900 and 1000 m a.s.l. The Mailuu-Suu River reports to the Syr Darya River which, in turn, feeds Lake Aral. Administratively, the area belongs to the Dzhalalabat province in the southern part of Kyrgyzstan, with a distance from the Uzbek border of around 25 km. Today, approximately 25 000 inhabitants live there, with a light bulb factory being the only employer of significance.

In and around the town, uranium was mined and milled from the late 1940s to the 1960s. Most of the waste dumps and tailings ponds are located in the valleys of the Mailuu-Suu River and its tributaries Kara Agach, Kulmen Sai und Aylampa Sai. Their proximity to the riverbeds, strong seasonal floods of rivers, steep slopes of a mountainous landscape, landslides and a pronounced seismicity[1] add up in varying degrees to the structural instability of a large part of the waste facilities. The area, typically covered with grass, is over-grazed which adds to the landslide risk and further reduces the water retention potential of the soil, increasing the frequency and magnitude of floods. Under these conditions waste material with elevated natural radioactivity is eroded and transported towards the denser populated parts of the Fergana valley and, further on, across the border to Uzbekistan, adding a politically sensitive cross-border aspect to the problem.

Investigation of the environmental and health impact of the uranium mining and milling wastes began after international attention had been drawn to the situation. Since then, numerous efforts have been undertaken to understand the environmental impact and develop appropriate remediation solutions, which have been financed by international organizations

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[1] Up to level 9 on the MKS (Medvedev Spoonheuer Karmik) scale.

such as the European Commission's TACIS program and the World Bank. In the following sections, the various investigation and remediation approaches and the current status of the remediation works will be presented and discussed. Currently, the design of remedial measures has almost been completed, and implementation of the most urgent measures is in progress.

The rest of this paper starts with a brief overview of the uranium mining and milling legacy at Mailuu-Suu (section 2), and provides a summary of the numerous projects over the past 15 years to tackle the environmental situation (section 3). The main results of the investigation programme and environmental impact assessment are presented in section 4. Section 5 discusses the selection procedure of the preferred remediation options for the most important waste sites, and section 6 presents results achieved and remaining challenges. As design activities, permitting procedures and the implementation of physical works are still in progress at the time of writing. This paper describes the situation at Mailuu-Suu as of autumn 2007.

LEGACY OF URANIUM MINING AND MILLING AT MAILUU-SUU

In the area of Mailuu-Suu, uranium mining and milling was carried out between 1946 and 1967 as part of the Soviet nuclear programme. Exploration and development of the uranium deposit of Mailuu-Suu began in late 1945, being one of the first in the Soviet Union's political reach. The deposit in Carnotite is of relatively low grade. Only scarce information on the ore characteristics, grades, production volumes and mining methods is available. Archives in Uzbekistan and Russia still have to be made fully accessible.

Underground mines were operated under a surface of around 36 square kilometers, subdivided into 5 mine fields, and accessible via 3 shafts and several adits. These operations resulted in 13 mine waste rock dumps left at the surface. Their total volume is around 0.9 million m^3. They are largely uncovered and partly exposed to erosion by the tributaries of the Mailuu-Suu River.

The ores were processed in 2 plants at Mailuu-Suu (later, ores were shipped to Kara Balta, west of Kyrgyzstan's capital Bishkek), together with ores from Eastern Germany (Erzgebirge area), China, Bulgaria and Czechoslovakia (Jachymov). The processing residues were stored in 23 tailings ponds with a total volume of around 2 million m^3.

The operations at Mailuu-Suu were closed between 1964 and 1968. Closure of the facilities was carried out according to Soviet standards: processing plants were mainly demolished (or used otherwise), underground workings secured and backfilled. In contrast to the waste rock dumps which were mainly left without any notable remediation, tailings were partly reshaped and received a mineral cover, even though many covers are incomplete and/or have been damaged.

The waste storage facilities differ significantly in their volume and footprint, but also in physical and chemical characterstics, in their exposure to fluvial erosion, seismic events and landslides, and thus in their significance in regard of environmental and health risks. While some of the 36 waste facilities are dry, with gentle slopes and stable, far away from both human settlements and rivers, others have been dumped within a steep, narrow riverbed where erosion carries away a significant portion of the wastes every year, or are nearly water saturated which reduces their structural stability under seismic events typical for the region, and could lead to a sudden release of pulpy radioactive tailings into the hydrographic system after dam failure.

HISTORY OF THE ENVIRONMENTAL REMEDIATION PROJECT

After closure of the operations in the late 1960s, the legacy of uranium mining and milling at Mailuu-Suu fell into oblivion until it received increasing international attention in the early 1990s. In 1992–1994, the first reports on sites of the Soviet nuclear fuel cycle appeared [1]. In negotiations with the Russian Government (1994), Kyrgyzstan raised the issue of environmental remediation of former uranium mining sites for the first time. In 1996–1998, a survey of the uranium mining legacy in the CIS was funded by the EU Commission's TACIS programme [3], which identified Mailuu-Suu as one of the foci of urgent environmental action. At around the same time, Kyrgyz media started to cover up the situation in Mailuu-Suu [2].

Soon, Mailuu-Suu became synonymous with the devastating environmental impact of environmentally unregulated uranium mining and milling in the former Soviet Union, with the common exaggerations of risk perception. Gerhard Schmidt, of the renowned Öko Institute in Darmstadt, Germany, warned in 1998 that “leaks from wastes could make water in the Fergana valley unfit to drink” [4]. The Blacksmith Institute listed Mailuu-Suu among the "World‘s 10 Most Polluted Places“(in 2007, it is still among the Top 30 [5]). The New Scientist (2002) stated that “flooding of Soviet uranium mines [i.e., Mailuu-Suu] threats millions”[6]. The massive media coverage has led to considerable public and political attention which helped to secure funding from numerous sources to solve the environmental problems at Mailuu-Suu. Activities include, but are not limited to the following:

- From 2000 to 2003, the EU Commission, through its TACIS programme, funded an in-depth investigation of the environmental situation and a feasibility study to develop appropriate remediation solutions [7] (“Remediation of Uranium Mining and Milling Tailing in Mailluu-Suu-District, Kyrgyztan”). This project which also included urgent stabilization measures of the Tailings dam N° 3 was carried out by a consortium led by SCK-CEN (Mol, Belgium) and still represents the most comprehensive data base for subsequent efforts.[2]
- Since 2004, IDA (the World Bank Group) has created the DHMP (Disaster Hazard Mitigation Project) which implements environmental remediation and public information and awareness activities in Kyrgyzstan. The DHMP is implemented by the Project Implementation Unit (PIU) within the Ministry of Emergencies (MoE).
- The IAEA Technical Cooperation Project RER9086 deals with the consequences of past uranium mining and milling practices. The countries that participated in these efforts are Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan [8].
- In the context of the DHMP, an Environmental Impact Assessment (EIA) was carried out by a Consortium of Jacobs Gibb and HCG Environment [9]. This EIA, together with a suite of associated assessments and reports (e.g., on seismology, water impacts, social assessment) were to provide the necessary information for the Environmental Assessment (EA) as required by the World Bank procedures.
- In 2005, the Consortium Geoconsult (Austria) – WISUTEC Wismut Umwelttechnik (Germany) was contracted for Component A of the DHMP, which deals with the design and supervision of remedial measures for the uranium wastes in the Mailuu-Suu region.

[2] A seamless continuation of the detailed work carried out by the SCK-CEN team was ensured by key experts of the 2000-2003 TACIS study who kindly provided invaluable background information to the authors of this paper [11].

- Starting in 2006, the German Federal Institute for Geosciences and Natural Resources (BGR) has funded a monitoring programme in order to improve the knowledge of the water impact of mining and milling residues on the water resources [10].
- In 2007, the German Federal Ministry of Environment and Nuclear Safety (BMU) devoted funds to a consulting, capacity building, training and know-how transfer project carried out by WISUTEC in order to complement the predominantly technical focus of Subcomponent A of the DHMP.

ENVIRONMENTAL SITUATION AND IMPACT OF THE TAILINGS AND WASTE DUMPS

The numerous studies and investigations of the environmental impact which have been carried out over the past decade, most notably the valuable data collection of the TACIS project [7, 12], and the additional results obtained by the authors of this paper within the DHMP [14], have revealed a picture which will be summarized in the following sub-sections.

Erosion

The most obvious and severe impact of waste facilities is due to the strong erosion of tailings and waste rock situated on the banks of the Mailuu-Suu river and its tributaries. Erosion of wastes is caused both by rivers and creeks on whose banks the wastes have been deposited, and by the unhindered runoff of precipitation during strong rainfall events and snowmelt. Most striking examples are the waste dumps (WD) N° 1 and 2 and tailings ponds (TP) N° 2 and 13, Figure 1.

FIG.1. Fluvial erosion of the dam toe of tailings pond N° 2 and 13 in the valley of Aylampa Sai, a tributary of the Mailuu-Suu River.

While erosion does not lead to a critical radiological impact today (i.e., incremental effective doses due to the mining and milling residues stay far below 1 mSv/a), it is the uncontrolled nature of the dispersion of radioactive mining and milling residues and the unpredictable accumulation of radioactive material on floodplains downstream which causes strong concerns. The transboundary nature of fluvial dispersion may also lead to political strains with neighboring Uzbekistan.

Another obvious issue is the bad state of maintenance of water diversion channels and ditches. Most existing channels have collapsed or are otherwise damaged, which adds to the erosive action of surface drainoff during and after heavy rainfalls and snowmelt.

Seismic instability

Tailings pond (TP) 3 which is situated in the Mailuu-Suu river valley, is unstable under seismic loads. TP 3 has been shown to be partially water saturated which is explained by springs beneath the tailings body. During the TACIS project [7], temporary stabilization measures in the dam area were carried out, and additional in situ stabilization techniques have been discussed, but under long term aspects relocation of the entire tailings pond is required.

Continuing erosion of loamy alluvial material from the hillslopes in the hinterland of TP 3 and its deposition on the tailings pond plateau leads to the build-up of a static load which further decreases the overall structural stability of the waste facility (Figure 2).

FIG.2. Tailings pond No. 3 seen from the cliff in its hinterland (note the Mailuu-Suu River behind the public road).

Landslides and mudflows

For the waste dumps and tailings, landslides are an indirect hazard in that they may block riverbeds. The raising water level will then inundate the waste dumps and tailings dams situated upstream of the blockage and decrease their stability. The Mailuu-Suu River is particularly affected. However, the extent to which landslide material can realistically block water courses and lead to the scenario described, is not entirely quantifiable yet. In order to achieve a more quantitative understanding of the impact of landslides, a landslide monitoring program has been developed by consortium member Geoconsult as part of the DHMP Component A.

The impact of the so-called Tectonic landslide on the cliffs above TP 3 on the tailings pond stability is discussed differently [7, 13]. Whether the landslide will reach the tailings surface after activation, threatening the stability of the entire structure depends on the quantitative results of the landslide monitoring program mentioned above.

Apart from their (indirect) impact on the uranium mining and milling wastes, landslides are a direct hazard to health and property of the population in the Mailuu-Suu area. A better understanding and prediction of the mechanisms and effects of landslides is therefore in the interest of the general welfare of the region.

Mudflows which occur in valleys such as the Kulmen Sai creek valley, close to waste dump WD 2, are similar to landslides in that huge amounts of material are suddenly sliding down the valley. They must be taken into account in the design of sustainable remediation solutions, otherwise they may severely damage riverbank strengthening measures and other man-made structures.

Impact of waste facilities on water quality

The impact of the waste facilities on fluvial water is barely measurable. Even though a weak increase of the radionuclide concentration in the Mailuu-Suu river can be observed [7, 14], the impact is far from causing a significant dose increment to downstream water users.

There are isolated occurrences of dam seepage water from tailings ponds which contain elevated concentrations of radionuclides. For example, the seepage of TP 16 contains around 24 mg/l uranium [14]. However, due to its remote location, there is no realistic usage scenario of the seepage (which can be further precluded by warning signs and diverting the seepage to the next creek in a controlled manner), so that there is no justification of further remedial action.

Radon and direct radiation

Apart from one waste dump (WD 5) and some isolated radiation hot spots due to damaged or incomplete covers, there are no sites which pose an acute radiological risk to the public.

WD 5 is located in a populated area with residential houses partly built on it. Long term radon measurements using track-etching detectors indoors and outdoors have shown that effective doses received by the public living near WD 5 may come close to, or even exceed, the 1 mSv/a reference value. Here, remedial measures are clearly required. Complete removal of the dump has been recommended and will be carried out.

Gamma-scans on the surface of waste facilities have revealed some isolated hot-spots of direct radiation, where the dose rate is well in excess of 1500 nSv/h. Examples are spots on TP 5, where the cover should be repaired, and WD 11 where obviously some low grade ore lies close to the waste dump surface. Typically, however, the ambient dose rate is well below 750 nSv/h [7, 14]. Even under conservative assumptions and use scenarios, effective doses stay far below 1 mSv/a, so that intervention cannot be justified.

Dust

Dust plays no significant role in the dose calculations. This is due to the fact that the tailings ponds are mostly covered with inert material, while the waste rock dumps are less prone to dusting (due to their coarser grain spectrum) and have a much lower activity concentration.

REMEDIATION MEASURES

General approach

Based on the environmental data which had been collected before the start of this project, and the additional investigations carried out during this project, and following an iterative evaluation and decision making procedure, all waste facilities in the Mailuu-Suu area were categorized in one of the following groups, according to the intervention measures recommended:

1. no action required;
2. remediation measures are recommend, but are of lower priority (such as removal of a supernatant water pond on a remote tailings pond, or slope stabilization of very small sites);

4. temporary stabilization measures, mainly riverbank strengthening in river sections with strong erosions, are urgently required;
5. long term solutions are needed to sustainably remove a major environmental and/or health risk, such as relocation of wastes to a safer disposal site.

As was already explained in section 4, acute radiological risks play only a minor role in the decision process, at least with respect to the costly long term solutions. The categorization was dominated by the obvious erosion and geotechnical risks. Nevertheless, the handling of radioactive material during the remediation measures requires the observance of guidelines and standards, among which the following IAEA standards are of particular relevance:

- RS-G–1.7 "Application of the Concepts of Exclusion, Exemption, Clearance";
- WS-G–1.2 "Management of Radioactive Waste from the Mining and Milling of Ores";
- RS-G–1.1 "Occupational Radiation Protection".

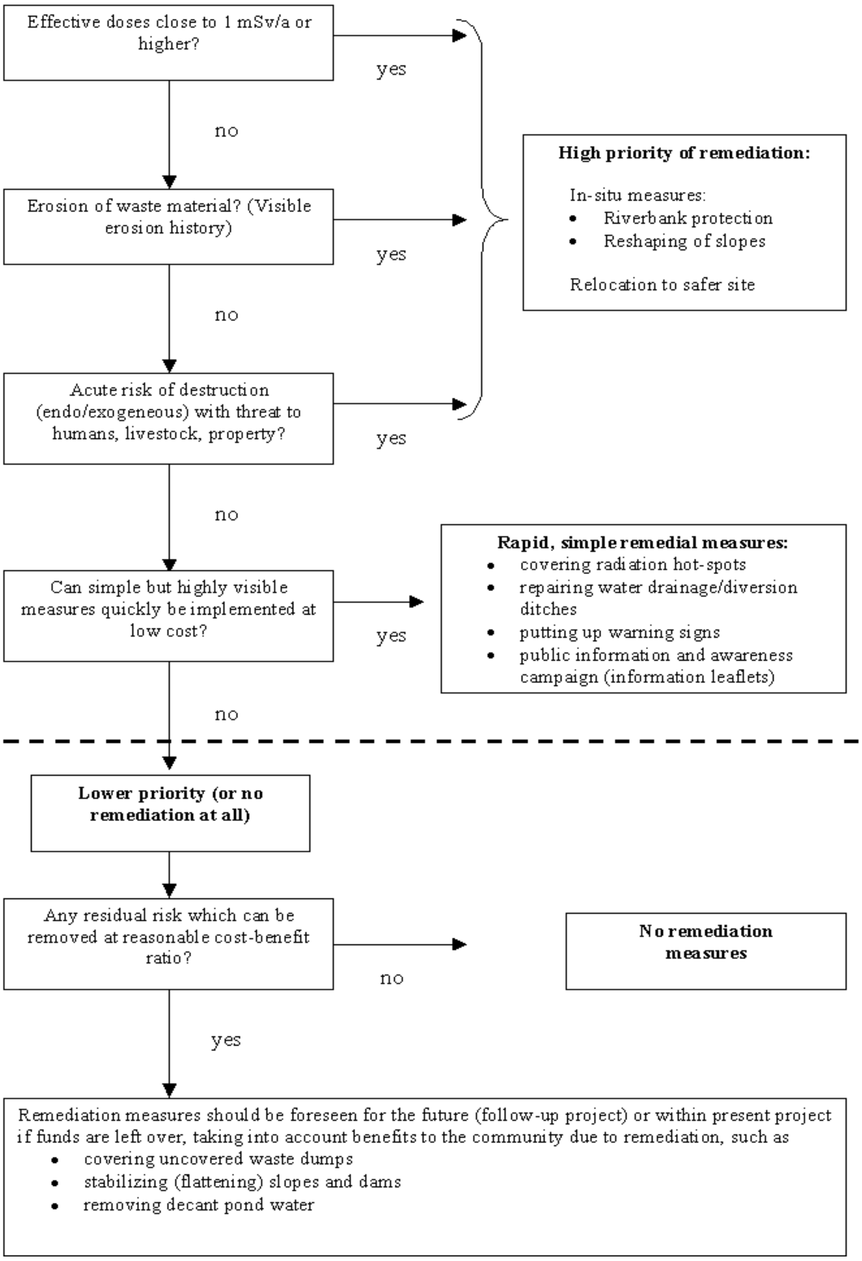

FIG.3. Decision procedure to categorize individual sites according to their priority.

Figure 3 shows the formal procedure to categorize the sites according to their priority for being remediated.

Of the 36 sites (13 waste dumps and 23 tailings ponds), 12 were found to need no intervention measures and 10 where remedial action was of lower priority. For the remaining 14 sites remediation was recommended with high priority in the first place. A second level of prioritization was needed to define a set of remedial measures which fit into the current budget and time frame of the DHMP. In the following sub-sections, we will focus on those measures which have been approved by the PIU for implementation within the current the World Bank funded project. They are summarized in Table 1 and explained in more detail below.

TABLE 1. SUMMARY OF REMEDIATION MEASURES WHICH ARE IMPLEMENTED DURING THE CURRENT PROJECT, AND FURTHER RECOMMENDED MEASURES OF LOWER PRIORITY

	Implementation during current project	**Lower priority**
WD 1	Relocation to WD 2	
WD 2	Reshaping of wastes (including material from WD 1), Riverbank strengthening	
WD 4	Warning signs	
WD 5	Relocation to TP 6	
WD 6	Riverbank strengthening	
WD 7		Relocation to safer site
WD 8		Retention wall
WD 11	Hot-spot cover	
WD 12		Relocation to safer site
TP 1, 4, 20-23		Riverbank strengthening
TP 2, 13	Temporary riverbank strengthening	Relocation to safer site
TP 3, 18	Relocation to TP 6	
TP 5	Riverbank strengthening, Repair of drainage ditches, Warning signs, Hot-spot cover	
TP 7	Riverbank strengthening, Repair of drainage ditches	
TP 8		Relocation to safer site
TP 14	Repair of drainage ditches, Warning signs	Removal of supernatant water pond
TP 16	Repair of drainage ditches, Warning signs	

It must be noted that the categorization of waste sites was an iterative process which took place in a highly dynamic project environment. Apart from technical considerations, the need to start physical, visible activities was a strong driver. On the other hand, due to the pilot nature of this project and the often conflicting national and international approaches and standards, the entire decision process has suffered from delays and setbacks which require considerable flexibility from all parties involved, not least the consultant. In this respect, training, consultation and know-how transfer efforts accompanying the technical project have become ever more urgent, which has finally led the German Ministry of Environment and Nuclear Safety to fund this additional component (see Section 3).

Simple, rapid and less expensive intervention measures

These measures include:

- placement of inert cover material of sufficient thickness on hot-spots of the gamma dose rate;
- repair of drainage ditches and water diversion channels;
- putting up warning signs; and
- a public information and awareness campaign.

Cover on radiation hot-spots

The gamma dose rate was measured on tailings ponds by the TACIS project [7] and on waste dumps by this team [14]. A soil cover was placed on waste facilities which are easily accessible to the public (more remote sites received warning signs, see below) and where the gamma dose rate on isolated hot-spots exceeded 1500 nSv/h. The thickness of the cover was calculated based on the experience of the Wismut project and numerical simulations of the attenuation of gamma radiation by natural covers [15]. Erosion protection considerations were also taken into account. The simple cover consists of two layers (from bottom to top):

- 30 cm compacted mixed-grained sandy-silty soil (loam);
- 20 cm compacted loamy gravel mixture, consisting of gravel (80...85%) and loam (15...20%);
- The top layer is covered with mawn grass which improves erosion control and assists quick revegetation.

Drainage and water diversion ditches

It is good engineering practice to divert surface water from tailings and waste dumps [16]. This improves the geotechnical stability of these structures and reduces the contact of undisturbed surface runoff with contaminated material which may lead to increased contaminant release through the water path. Existing channels are cleaned and repaired, in some cases new channels are built. The cross section and slope of the channels corresponds to the hydraulic conditions. Of the various variants compared by the consultant, superficial ditches lined by natural materials such as stones, wood or plants were chosen.

Warning signs

Signs which make the public aware of radiation risks, warn against using material and water are erected, according to international practice. [17] Locations of warning signs are gamma dose rate hot spots (>1500 nSv/h) at remote waste sites where a cover is not justified, and along seepage channels with elevated radionuclide concentrations in the water which should not be used for human consumption, irrigation and cattle watering. Spacing between warning signs is around 150 m. The signs are visible from both sides, the typographical design of the signs is clearly legible also to the visually disadvantaged (large letters, high contrast), and contains the use and access restrictions as well as the contact addresses of the Ministry of Emergencies for further information.

Public information and awareness campaign

Informing the public about the current situation is good practice in the field of radiation protection. Following a recommendation of the ICRP [18], general information on the level of exposure should be made available if the likely effective dose received by members of the public is on the order of, or below, 1 mSv/a (for doses exceeding 1 mSv/a, the ICRP recommends more detailed information on ways to reduce the exposure of the public, but this situation does not occur at Mailuu-Suu). One-page information leaflets which are distributed to all households have been developed with the following content:

- Short description of the waste sites and the risks to human health and environment;
- Short description of the remediation measures undertaken to mitigate risks at the waste sites;
- General restrictions on land-use of the tailings and waste dumps;
- Precautions which should be taken seriously;
    - No use of seepage or drainage water for drinking and cattle watering;
    - No use of waste dump and tailings material for construction;
    - No agricultural use of tailings and waste dumps.

Erosion protection

As was discussed above, erosion of mining and milling wastes and their uncontrolled dispersion in the environment is of greatest concern and requires urgent action. Erosion protection measures are carried out either as rapid intervention with a temporary scope (the wastes shall eventually be relocated to a safer disposal site), or as permanent, sustainable solutions. The strongly eroded tailings ponds 2 and 13 in the Aylampa Sai valley fall into the first category, while the waste dumps 1 and 2 (Kulmen Sai valley) and 6 (Kara Agach valley) fall into the second.

The general approach to erosion protection is adapted from the experience of the Austrian consortium member Geoconsult in alpine environments. The technical measures include the use of gabions and Reno mattrasses, energy dissipators and similar structures known from alpine rivers.

At WD 6, it was possible to design the riverbank strengthening measures in a way to avoid any contact of workers with radioactive waste rock, by confining the construction works to a narrow strip on both sides of the riverbed sufficiently far away from the waste rock toe. This approach also helped to simplify and speed up the permitting process.

On the contrary, sustainability of erosion protection measures in the Kulmen Sai valley at WD 1 and 2 required that WD 1 with a volume of about 150 000m³ is relocated to WD 2 (around 1 km upstream) and the entire waste rock body is reshaped so as to achieve a long term stable surface contour, before the riverbank can be enforced and stabilized. An additional complication comes from the mudflows which threaten the entire structure and must be kept at bay by a special mudflow diversion dam. The amount of radioactive material to be moved and the risk that material may be spilled into the Kulmen Sai River necessitated the development of detailed Environmental Management, Monitoring, Radiation Protection and Health & Safety Plans.

The design of erosion protection measures for the dam toes at TP 5 and 7 which are both located on the western bank of the Mailuu-Suu River depends on the results of an elaborate geotechnical investigation programme of the landslides which may block the Mailuu-Suu riverbed. The description of the investigation programme developed by consortium partner Geoconsult and the related modeling approaches is beyond the scope of this paper.

Relocation of waste facilities including Tailing pond N°3

For 7 tailings ponds and waste rock dumps, relocation to a safer disposal site would be the most sustainable solution (Table 1). Within the current project, the decision has been taken to relocate TP 3 (125 000m³ including part of the abutments and bedrock), the small adjacent TP 18 (3000m³) and WD 5 (53 000m³) from the Kara Agach settlement to a safer site.

A constraint of the selection process was that no virgin land should be used for waste disposal, which left only sufficiently large waste facilities for further consideration. There were a number of options for final disposal sites, which included TP 15, located on the high plains several kilometers east of the Mailuu-Suu river and which is the safest option with respect to fluvial erosion.

The preferred final disposal site and the optimal relocation technology are inseparably intertwined, as are the relocation of two waste types (coarse waste rock from WD 5 and fine tailings from TP 3) and the waste encapsulation and cover design. The decision for the preferred option was a complex, iterative process which took the following criteria into consideration:

- Cost;
- Long term stability;
- Technical feasibility and technical risks;
- Impact on public traffic;
- Acceptance by the public and regulators.

TP 6, a tailings pond north of the towns of Mailuu-Suu and Kara Agach, on the western bank, with a flat plateau of around 6 hectares, was chosen as final disposal site. Being located high enough to be protected from erosion by the Mailuu-Suu River, it is easily accessible which leads to a major cost advantage over other options. The drawbacks of TP 6 (need to repair a bridge for haulage, construction of an access road from Kara Agach to TP 6 to haul WD 5 material, landslides affecting the haul road section on the eastern bank of the Mailuu-Suu) are manageable.

In the feasibility phase, shear vane investigations were carried out on a grid of roughly 20 x 20 meters mesh size. They provided a precise quantitative picture of the inhomogeneous, partly water saturated tailings [19] which is one of the technological challenges of the project. Alluvial material from the existing cover on TP 3 will be mixed with the wet, soft tailings to provide a material which transportable by trucks.

Of a wide variety of relocation technologies which, among others, also included hydraulic transport, trucks with watertight moulds and tarpaulin covers were selected. Hydraulic transport would have required an additional step of removing the excess water at the disposal site. Concerns about the disruptive effect of massive truck movements on public transport, safety risks associated with the transportation of radioactive material on public roads, stability of the abutments at the present location of TP 3 and water management are addressed in the design.

With its favourable hydraulic and geotechnical properties, the waste rock from WD 5 is suitable as dam material for the final disposal site and is integrated into the cover design. The final cover will consist of a store and release system [20] (thickness of 100cm on the dam slopes and 150 cm on the plateau, of which the lower 50 cm will be compacted) and a vegetation cover.

RESULTS ACHIEVED, REMAINING CHALLENGES AND CONCLUSIONS

The overarching objective of the remediation project in Mailuu-Suu is to protect the population of the Mailuu-Suu area and riparian users downstream including Uzbekistan, from the risks caused by the residues of former uranium mining and milling activities. It can be concluded that the practice and experience developed during other remediation projects on uranium mining and milling sites not least including the Wismut project in Eastern Germany, combined with the erosion protection and landslide management experience from alpine regions, can be applied and site-specifically adapted to the situation in Mailuu-Suu, to achieve this objective.

The results achieved so far are:

— The temporary riverbank strengthening measures at TP 2 and 13 and the stabilization of the Kara Agach riverbed at WD 6 have been completed. The quick measures described in Section 5.2 (covering radiation hot spots, water diversion channels, warning signs and information leaflets) are in progress, as are the relocation of WD 1 to WD 2 and the subsequent reshaping and riverbank protection at WD 2;
— The access road from Kara Agach to the new disposal site of TP 6 is under construction. Relocation of WD 5 to TP 6 will begin early in 2008, using this newly built road; and
— For relocation of TP 3 and 18 to TP 6, the design and EIA have been submitted to the MoE for review (including the road bridge overhaul).

The scarcity of suitably equipped and qualified contractors for topographical surveys, geotechnical investigations and (radio-) chemical laboratories, the lack of experience among regulators and a slow flow of information between the stakeholders are limiting factors and have clearly been underestimated in the preparation phase and by the authors of this paper.A sufficient local skill base of field investigation and analytical methods is absolutely required to carry out the current remediation tasks, particularly if environmental projects are to be carried out in the future with national resources.

The need of training, know-how transfer and capacity building activities has become increasingly obvious during the implementation of the technical project. The remediation project at Mailuu-Suu is the first of its kind in Kyrgyzstan and is seen as a pilot for other remediation projects in the region. This requires the optimal involvement of regulatory authorities, governmental and local agencies, NGOs, and the local population, in order to create a common understanding of the environmental situation, technical approaches with their benefits and drawbacks, and the institutional capacity requirements including a clear definition of responsibilities and the necessary permits and licenses requested under many, often conflicting, national regulations.

Modern international technical standards and approaches (e.g., related to cover systems on radioactive residues) are different from national standards, which, in turn, often reflect outdated Soviet standards. This may significantly delay permitting procedures and consume valuable resources. Training of decision makers and regulatory authorities can help to create a better informed environment for decisions and permits. For example, monitoring and health/safety requirements issued by the local or even national authorities often differ from what is seen as appropriate based on international best practice, given the moderate level of radioactivity and realistic exposure scenarios. Early transfer of know-how and best practice, well before the physical works commence, is therefore essential to avoid costly interruptions of the works.

Finally, local contract management and construction supervision skills are essential in order to implement remediation measures according to international standards (e.g., the FIDIC standards of construction contract management).

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ACID ISL OF URANIUM IN CZECH REPUBLIC

V. Benes
DIAMO s.p., Czech Republic

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Abstract

This paper describes the history and development of acid in situ leaching (ISL) technology for exploitation of uranium ores on Bohemian Cretaceous Basin in the Czech Republic. The geological and hydrogeological conditions are briefly described and evaluated. The uranium production started in 1969 and the production was suspended in 1995. The development of the ISL technology and it becoming state-of-the-art is discussed. In addition, the paper focuses on various aspects of the well completion, layout of the wells in the field, composition of the leaching agent, processing of the solution, consumption of chemicals, production of uranium, recovery and effectiveness of the leaching process. The environmental impacts of the mining and remediation are outlined and discussed. The necessity of simultaneous application of mining and remediation technologies is the most valuable lesson learned and the most important recommendation for any future application of acid ISL under comparable conditions.

INTRODUCTION

The in-situ leaching (ISL) technology of the uranium recovery has been performed in Czechoslovakia for 25 years. The pilot plant experiments with ISL were performed in 1967, and in the following year the first leaching field was put into operation. Afterwards the rapid progress of this mining method followed in parallel with research work and the gradual solution of technical and technological problems. During this period extensive experience with the planning and operating of the ISL technology was obtained. In the course of this application it was necessary to develop a theory of the relevant underground processes, to work out the methods of the geotechnological evaluation of the deposit and to solve a great number of specific technological problems. This led to a certain degree of stabilization of the drilling technology and also of the solutions processing on the surface. In 1995 the leaching fields occupied an area of about 6 000 000m^2 and there were about 7000 technological wells and numerous monitoring wells within that area. The importance of environmental aspects was not intensified until the decision to stop the enlargement of the leaching area in 1992.

GEOLOGICAL CONDITIONS

The ISL was applied in the Straz deposit in North Bohemia [3]. The deposit is situated in sedimentary rocks of the so-called Straz block of the Bohemian Cretaceous basin which contains a significant reservoir of drinking water in the European range. The Straz block is a tectonically limited unit inside of the Cretaceous basin in which several uranium deposits are situated (Figure 1). The Hamr deposit, which was exploited by classical deep mining, is situated in the neighbourhood of the Straz deposit.

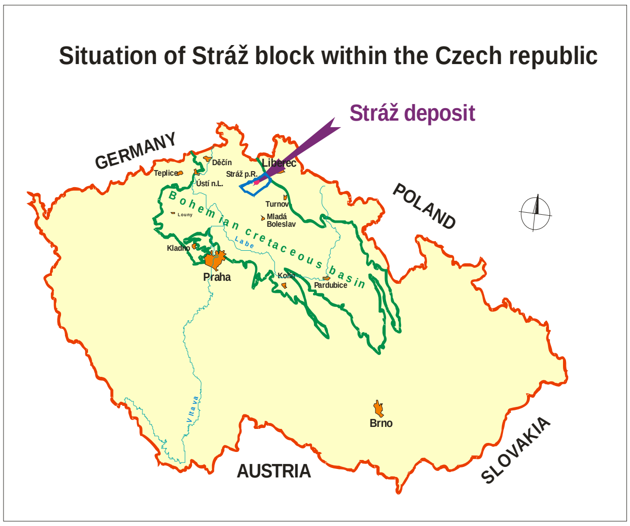

FIG.1. Location of the Straz deposit.

The thickness of the Cretaceous formation in the Straz block varies from 200 to 250 meters. The basement consists mainly of grained rocks. The Cretaceous sedimentary complex is formed by two stratigraphic units. The lower, the Cenomanian formation contains the uranium ore mineralization. On its basis the freshwater sediments are locally developed (in depressions of the paleorelief). They are overlain by the washout sediments with a thickness of 0.5 to 5.0m. These sediments are formed by changing layers of different composition, grain size and permeability (breccias, sandstones, siltstones, often with admixtures of organic matters and pyrite). They often contain uranium ore mineralization. Above these there is a stratum of the friable sandstones (thickness 20–25 m). These sandstones are very good permeable and uranium mineralization is located in their basal part. The upper part of the Cenomanian sequence is formed by more compact and less permeable fucoid sandstones (thickness 40 m). The basis of the Turonian sequence is formed by a 60 m thick formation of poorly impervious siltstones and marly limestones. Above them there are permeable thick-bedded sandstones which often reach the surface.

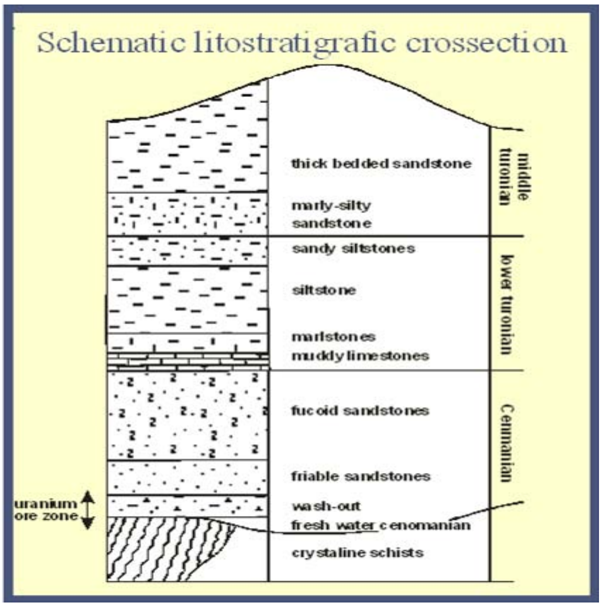

FIG.2. Schematic cross-section of Straz deposit.

The most economically important uranium minerals and uranium-containing minerals of these ore deposits are uranium oxides (uraninite UO_{2+x}), ningyoite ($CaU(PO_4)_2 . nH_2O$) and hydrozircon ($Zr(Si_{1-x}O_{4-4x}(OH)_{4x}).n H_2O$).

The size of the individual grains of uranium minerals usually does not exceed 1 to 2μm. The mutual ratios of these minerals change in the area. The leachability of uranium is directly connected with this. The technological properties of the ore are unfavourably affected especially by the content of hydrozircon and often by accompanying metacolloidal baddeleyit.

In the Straz block there are two divided groundwater levels. The upper aquifer is bound by good permeable sandstones of the middle Turonian and is a significant reservoir and source of drinking water. These waters are of the bicarbonate calciferous type. The groundwater level of the Cenomanian aquifer is characterized as artesian. The confining layer is formed by siltstones of the lower Turonian. From the hydro chemical point of view the Cenomanian waters in their natural state are not affected by mining interventions. They differ from the waters of the Turonian sequence by containing of Ra^{226}. The safety standard for drinking water is exceeded about one hundred times.

The most permeable rocks of the Cenomanian are the friable, poorly cohesive sandstones with the coefficient of filtration k_F = 2 to 8 meters per day. Due to the influence of their detailed stratification, these rocks show a characteristic anisotropy of permeability. The petrographically more varied washout sediments with alternating small layers of rocks with different grain sizes have even higher anisotropy but lower permeability. The value of the filtration coefficient here is in tens of meters per day similar to fucoid sandstones.

TECHNOLOGY OF ISL

The results of laboratory research and the parallel knowledge obtained from the operation showed very quickly, that the conditions for underground leaching in the Stráž deposit are extremely difficult [4]. The part of uranium mineralization occurs in poorly permeable rocks, often in contact with permeable layers. There are usually good leachable ores which are leached, unfortunately only under diffusion conditions. Another part of uranium mineralization in permeable rocks is very difficult to leach. The reaction takes place very slowly here and it can be accelerated practically only by a higher concentration of the leaching reagent.

Under these conditions only acid leaching could be applied with any success. The main component of the leaching solution was sulphuric acid in an average concentration of about 5%. The leaching solution was also enriched by an oxidant. NO_3^- ions as the overbalance from ion exchange resin regeneration were used for oxidation, together with ferric ions as a result of acid leaching. The filtration transport of dissolved components is relatively fast, so the comparatively slow chemical reactions and the diffusion processes played the leading role in the whole process. For this reason the borehole network of new leaching fields was gradually adapted to the final optimal density. The total leaching period took 15–25 years with gradually decreasing addition of leaching reagents and falling uranium concentrations of uranium in solutions.

The composition of the leaching agent and the batching of sulphuric acid were essentially modified during ISL technology application. The original technology didn't differentiate the technological properties of ores in different parts of the deposit. The improvement of the technological evaluation methodology together with higher knowledge about the leaching process enabled the optimization of leaching technology by means of mathematical models. Different batches of sulphuric acid were applied to individual wellfields after all. The total batches were from 2000 t to 14 000 t per 10 000 m^2. They were differed also in the time distribution dependening on technological and economical properties of each wellfield.

During the adjustment of the well networks and the changes of the pumping technology, a number of different patterns have been tested, e.g. polygonal and linear ones [2]. The first well fields were constructed with tetragonal pattern and the basic distance between wells was 28 m. This well net was thickened to 20x20 m and even to 14x14 m on areas with the rich uranium mineralization. The injection and recovery wells alternated regularly. The newer well fields were built with a parallel pattern 25x40 m and later 20x50 m based on the higher quality of drilling and casing and the higher knowledge of the leaching process. The last step in the development of well patterns was connected with the application of submersible pumps. These type of well patterns were formed by lines of recovery wells with the diameter 200 mm and by double lines of injection wells with diameter 90mm. The distance between lines was about 100 m, the distance between recovery wells was from 60 m to 80 m and the distance between injection wells in one line was about 12 m, it means 6 m in axis. The well network was also optimized with respect to the topographic inequalities in some parts of the deposit. Under favourable conditions it was possible to farm on the agricultural soil between individual well lines during the leaching process.

FIG.3. Wellfields with pattern 20x50 m (left) and well lines at spacing of 100 m (right).

The long period of activity of the individual well fields also made it necessary to develop very safe well constructions. They must guarantee an almost perfect safeguard against the possible contamination of the upper Turonian aquifer by technological solutions. From 1978 the injection wells were passed through the Turonian sequence with a double casing – on the outside by steel, from within by an acid-resistant casing pipe. Until 1984 pumping was performed exclusively by air-lifts and the construction of both the recovery and injection wells was similar. Since 1985 submersible pumps with a diameter of 4–6" have gradually been put into operation. These pumps required wells with diameter ca 200 mm and inside casing by stainless steel. The well completion consists of under reaming, screening and gravel packing.

The difficult conditions made it necessary to work out an original methodology for the technological evaluation of the ores. It was based on special laboratory tests made on core samples from exploratory wells. They involved both short term and long term (up to 1000 days) leaching and filtration tests which were used to determine the kinetics of the chemical reactions. Similarly the rate of diffusion's transport of the reagent and dissolved components were fixed. The filtration parameters of rocks were determined indirectly by means of regression analysis from the chemical composition. The resulting values served as input data for the mathematical models.

The mathematical models were used for designing and optimization of the operation. They described the geotechnological structure of the rocks, the groundwater flow, the transport of components, the chemical reactions taking place in sandstone deposits and also the economic relations. The models also utilized the data collected in extensive databases referring to geological and technological features and the operation data of individual wells and leaching fields.

The pipelines on the surface were mostly made of polyethylene tubes. Stainless steel was used only in sections with higher pressure. The local pumping stations were built for solution transport from greater distances or at super elevations. The pipelines were equipped with a control system to signal any failures.

For the uranium separation from the solutions at the surface the classical ion exchange technology was used. Strong basic anion exchange resins were used with respect to the composition of recovery solutions. The original technology with ion exchange in fixed bed columns was gradually replaced by the continuous counter current sorption and regeneration technology. The proper development of the surface technology, of sorption and regeneration apparatus, complementary technologies and the development of the most suitable regeneration solution increased the efficiency of the surface processes and decreased the total consumption of chemicals. The resin loading strongly depends on the acidity of the recovery solution and in these conditions it was low, amounting approximately to 10 $g.dm^{-3}U$. The solution based on HNO_3 and NH_4NO_3 was used for ion exchange resin regeneration. The nitrate ion which passed from the sorption partly to the leaching cycle was utilized in the leaching technology at the same time as oxidizing reagent. The uranium concentration in the eluate was about 5-10 $g.dm^{-3}$.The eluate was neutralized by ammonium. The ammonium diuranate was the final product of the hydro chemical uranium extraction after filtration, washing and drying.

THE RESULTS OF ISL

About 30 wellfields were in operation until 1996, the area of each of them was from 100 000m^2 to 350 000 m^2. The whole area of the wellfields was nearly 6 000 000m^2. Two processing plants had a total flow capacity of 60 000m^3 per day and the production capability of 800t of uranium per year.

From 1985 only part of the oldest well fields was alternately operated. The wellfields were split into three groups with different technological mode. The oldest wellfields were working without the addition of sulphuric acid; the leaching solution was only circulated with the separation of uranium in the processing plant. The second group (from 5 to 10 years old) was operated with small batches of sulphuric acid, the acidity of the leaching solution was from 20 to 35 $g.dm^{-3}$ and the circulated volume was low. The newest wellfields were operated with greater circulation and the concentration of sulphuric acid in the injection stream was from 40 to 100 $g.dm^{-3}$.

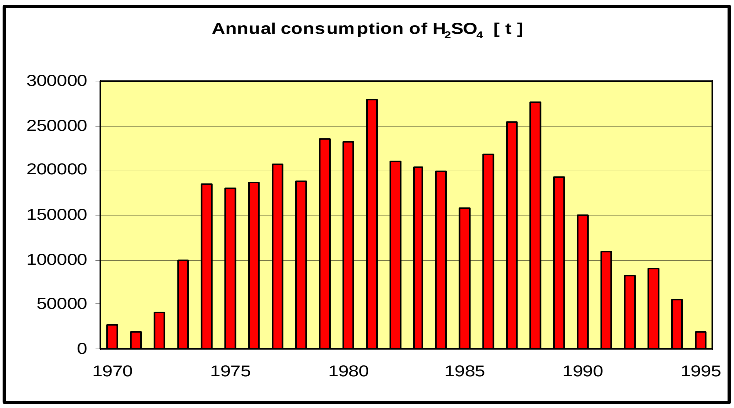

FIG.4. Annual consumption of sulphuric acid.

The sulphuric acid was consumed by the reaction with carbonates, alum silicates and iron minerals. The resulting reactions produced slightly soluble to soluble metallic sulphates which contributed to a build-up of SO_4^{2-} anions and polyvalent metal cations in the leaching solution. The nitric acid was consumed by oxidation reactions with uranium minerals, sulphide minerals and organic matter. The ultimate products of the oxidation reduction reactions were not quite well defined. Nitrous and other intermediate nitrogen oxides products as well as nitrogen could be present in the solution. The ammonia was not consumed in the process. The hydrofluoric acid was used for cleaning the injection wells. All of the HF was probably consumed by reaction with gangue minerals. The average chemical composition of the recovery stream resulting from the reaction of all the chemicals in the wellfields is shown in Table 1.

TABLE 1. AVERAGE CHEMICAL COMPOSITION OF THE RECOVERY STREAM

Major constituents	$g.dm^{-3}$	**Minor constituents**	ppm
H_2SO_4	15 – 30	Si	100 – 200
SO_4^{2-}	40 – 65	P	50 – 150
NH_4^+	1,0 – 1,5	K	40 – 70
Al	4,0 – 6,0	Zn	30 – 50
Fe	0,5 – 1,5	Mg	20 – 30
NO_3^-	0,3 – 0,8	Ni	20 – 30
F^-	0,1 – 0,3	V	10 – 15
Ca	0,2 – 0,3	Cr	5 – 15

The average uranium concentration in the recovery stream was about 30 pm on the oldest fields and about 100 ppm on new fields. High uranium concentrations, about 500 ppm, were reached on several wellfields during the first year of operation. The total production of uranium was over 15 000 t during the production period from 1968 to 1995 (Figure 5).

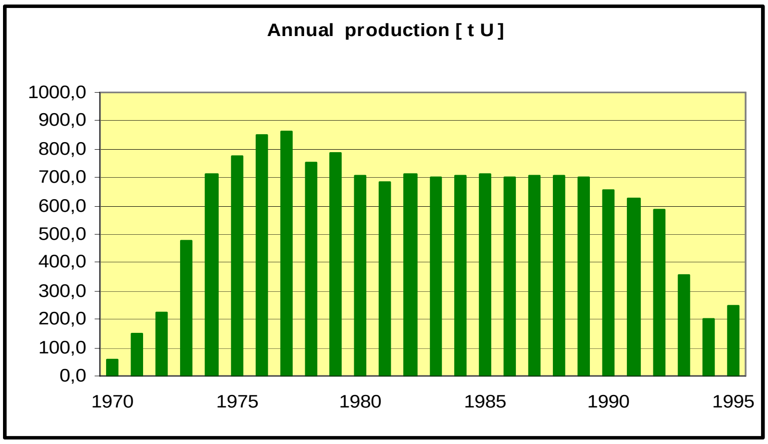

FIG.5. Annual production of uranium.

The uranium recovery was significantly different on individual wellfields. It depended on the technological type of uranium mineralization and on the selected technological mode. The technological modes were designed on the basis of technological and economical modelling. On wellfields with poor and difficult leachable resources of uranium there were technological modes with small batches of sulphuric acid, a short production period and a low predicted recovery of uranium. The opposite modes were applied on wellfields with relatively rich and more easily leachable uranium resources. In this case economical conditions enabled to apply bigger batches of sulphuric acid and the recovery of uranium could reach up to 80 per cent of the geological reserves. Geological specification and details about operation of individual wellfields are presented in Table 2.

It was not possible to keep the technological solutions within the boundaries of the leaching fields owing to complicated hydrogeological conditions caused by close neighbourliness of the deep mine Hamr and of certain permanent over-balance of the circulating leaching solutions (addition of chemicals and waste waters from the processing plants). The permanent solutions overbalance had a very important negative impact to the scope after mining groundwater restoration. Although it was “only” 3–5% of circulated volume, the increase in the amount of contaminated solutions was over 10 million m^3 after 25 years of ISL mine operation, which is more than 10% of original deposit water volume.

Thus the Cenomanian aquifer formed an extensive aureole of contaminated solutions. There was about 90 million m^3 of the groundwater with a concentration of total dissolved solids (TDS) 10–60g.dm^{-3} and 90 million m^3 with a concentration of TDS below 10 g.dm^{-3} which contained about 5 million tonnes of dissolved substances in the Cenomanian aquifer at the end of 1995.

TABLE 2. GEOLOGICAL SPECIFICATION AND OPERATIONAL DETAILS OF INDIVIDUAL WELLFIE

Well field No	Area [m^2]	Geological reserves [t U]	Thickness of U mineralization [m]	Average content of U [%]	Number of production wells ∅90 mm	∅200 mm	Time of operation [years]	The batch of H_2SO_4 [kg.m^{-2}]	Recovery of U [%]
VP-4	90120	1056,8	7,55	0,073	226		26	1417	50,49
VP-7A	288200	1686,6	6,25	0,044	323		20	834	46,04
VP-7B	128600	1168,5	7,93	0,054	156		20	1685	47,64
VP-8A	235180	1603,0	7,70	0,041	326		22	969	43,61
VP-8CD	342020	1380,4	4,70	0,040	353		18	693	48,01
VP-8E	176630	1432,4	4,82	0,079	178		19	1082	47,78
VP-8F	167560	1034,6	4,39	0,066	221		17	1052	37,81
VP-9A	152450	798,4	5,31	0,046	319		17	1167	40,01
VP-9B	229350	1055,3	5,03	0,043	449		19	772	62,95
VP-9C	76560	461,8	5,53	0,051	105		18	1045	58,14
VP-9D	113600	587,8	4,27	0,057	154		20	775	34,64
VP-10A	93820	1048,5	8,47	0,062	192		18	921	48,33
VP-10B	90660	416,6	5,58	0,036	145		13	647	32,65
VP-10C	101040	268,0	3,10	0,038	281		13	1052	76,03
VP-11	68940	538,6	6,76	0,054	65		10	1489	46,73
VP-12A	98680	930,4	8,45	0,052	123		17	517	38,26
VP-12B	210420	1064,2	4,30	0,055	143		14	454	46,15
VP-12C	50960	511,1	5,85	0,081	39		12	131	34,18
VP-12D	155250	1215,0	5,61	0,066	177		12	412	34,64
VP-13A	102920	227,4	3,99	0,026	80		14	408	70,33
VP-13B	222130	564,1	2,41	0,049	183		12	421	22,97
VP-14	305050	1917,4	5,56	0,054	266		13	793	47,71
VP-15	208490	832,5	4,72	0,040	117	8	12	770	89,10
VP-16	231570	1223,8	4,17	0,063	91	9	11	666	54,40
VP-17	263230	1325,1	3,53	0,073	135	10	9	377	11,24
VP-18	317040	1879,7	4,75	0,059	179	15	10	487	33,08
VP-19	90170	893,9	6,26	0,078	68	5	9	584	18,00
VP-20	208220	941,3	3,34	0,067	135	11	6	640	37,12
VP-21	201020	1353,3	4,80	0,068	97	8	5	102	19,70
VP-22	198560	449,7	3,16	0,036	62	5	4	28	31,30
VP-23	274610	1222,2	4,14	0,052	164	15	8	369	50,22
VP-24	246680	821,2	2,77	0,057	177	16	7	449	68,10

Contamination of the Turonian aquifer was also found, but in to a small extent. This contamination was caused both by injection of the technological solutions into the wells with damaged casing or with imperfect insulation of both aquifers, and by local surface leakage of the technological solutions into the original soil horizon. Contamination of the Turonian aquifer was mostly bound in the form of horizontally or vertically limited lentils. Representation of individual components in the solutions corresponded to technological solutions composition.

RESTORATION

The end of uranium mining and the start of the remediation of the ISL mine on the deposit Stráž pod Ralskem is one of the greatest ecological projects in the Czech Republic [5, 6]. If the remediation works were not carried out, there would be a real danger of a negative affect on the reserves of high quality waters in the North-Bohemian cretaceous basin, which would manifest in the time horizon of several thousand years and also in endangering the Elbe River.

Based on CR Government decision the main principle of remediation is treatment of contaminated water on the surface with minimization of produced solid wastes, discharge and re-injection of cleared water.

Turonian solutions in concentration below 10 $g.dm^{-3}$ TDS are cleaned in the amount of approximately 1,5 $m^3.min^{-1}$ on neutralization station by lime precipitation technology. No extra technology equipment has to be made up for Turonian remediation. At present most contamination is removed from Turonian aquifer. The target is to reach the water quality given for a drinking water source in the whole area.

The huge desalination station [5], operated for treatment contained strongly contaminated Cenomanian water (about 50 $g.dm^{-3}$ of TDS) from 1996. The station consists of two parts, evaporation with an average capacity of $4m^3.min^{-1}$, evaporated water and crystallisation of salts from a concentrated solution. Clean water is discharged to the nearby river. The product of crystallisation is ammonium aluminium sulphate $NH_4\ Al(SO_4)_2.12H_2O$ which is afterwards reprocessed to commercial products – aluminium sulphate and fertilizers. Weakly contaminated Cenomanian water (up to 10 $g.dm^{-3}$ TDS) is treated in an amount of 2 $m^3.min^{-1}$ together with Turonian water by lime precipitation technology.

Remediation itself will take the next 15 to 20 years [7]. The target is to reach the required concentration limit in the Cenomanian aquifer after the end of remediation. The preliminary established concentration limit is 8 $g.dm^{-3}$ of the total dissolved solids in the Cenomanian aquifer. This concentration limit has been set up on the basis of current available data on solutions composition and risk rate of their individual components.

SUMMARY

The plant for the chemical extraction of uranium in Stráž was the largest in Europe and was comparable to other similar plants in the world. During 25 years of operation a great number of original technological and technical devices for the proper production and the later remediation of the affected area have been developed. Vast experience was gained in the methods of control for groundwater hydraulics over large areas (designing and operation of hydraulic barriers, pumping centres, plants for the desalination of contaminated water etc.). The results of long-term operation demonstrate the possibility to mine similar deposits with good effectiveness with total unit costs in the range of $80 to 120 per kg of uranium including the restoration costs.

The main problem of the next utilization of ISL technology is to solve the groundwater restoration after finishing the extraction of uranium and to design environmentally safer technology. It is possible to recommend some measures as the most valuable lessons learned to decrease the difficulties with after mining restoration. From operational results it is clear that it is necessary to remove the volume overbalance of processing plant technology from the leaching circuit. The injection of unnecessary chemicals underground (e.g. ammonia) could result in substantial problems during the ground water treatment. It is strongly recommended to start the restoration of groundwater in parallel with uranium production in speculations about the future ISL uranium mining on other deposits of the North Bohemian Cretaceous Basin. The permanent under balance of injected solutions will guarantee the operation without any spreading of leaching agent over the deposit boundary. Together with the continuous removal of parts of leaching products from underground, it will prepare reasonable conditions for after mining groundwater restoration. This should be the precept for any new acid ISL project all over the world.

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THE NEW GENERATION OF URANIUM IN SITU RECOVERY FACILITIES: DESIGN IMPROVEMENTS SHOULD REDUCE RADIOLOGICAL IMPACTS RELATIVE TO FIRST GENERATION URANIUM SOLUTION MINING PLANTS

S. H. Brown
CHP, SHB INC., Centennial, Colorado

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Abstract

In the last few years, there has been a significant increase in the demand for Uranium as historical inventories have been consumed and new reactor orders are being placed. Numerous mineralized properties around the world are being evaluated for Uranium recovery and new mining / milling projects are being evaluated and developed. Ore bodies which are considered uneconomical to mine by conventional methods such as tunnelling or open pits, can be candidates for non-conventional recovery techniques, involving considerably less capital expenditure. Technologies such as Uranium In Situ Leaching/In Situ Recovery (ISL/ISR – also referred to as "solution mining"), have enabled commercial scale mining and milling of relatively small ore pockets of lower grade, and are expected to make a significant contribution to overall world wide uranium supplies over the next ten years. Commercial size solution mining production facilities have operated in the US since the late 1960s.

However, current designs are expected to result in less radiological wastes and emissions relative to these "first" generation plants (which were designed, constructed and operated through the 1980s) which typically used alkaline leach chemistries in situ, open to air recovery vessels and high temperature calcining systems for final product drying. Improved containment, automation and instrumentation control and use of vacuum dryers in the design of current generation plants are expected to reduce production of secondary waste byproduct material, reduce Radon emissions and reduce potential for employee exposure to uranium concentrate aerosols at the back end of the milling process.

In Situ Recovery involves the circulation of groundwater, fortified with oxidizing and complexing agents into an ore body, solubilizing the uranium in situ, and then pumping the solutions to the surface where they are fed to a processing plant (mill). Processing involves ion exchange and may also include precipitation, drying or calcining and packaging operations depending on facility specifics. This paper presents an overview of the ISR process and the health physics monitoring programs developed at a number of commercial scale ISL / ISR uranium recovery and production facilities as a result of the radiological character of these processes. Although many radiological aspects of the process are similar to that of conventional mills, conventional-type tailings as such are not generated. However, liquid and solid byproduct materials may be generated and impounded. The quantity and radiological character of these by products are related to facility specifics. Some special monitoring considerations are presented which are required due to the manner in which radon gas is evolved in the process and the unique aspects of controlling solution flow patterns underground.

The radiological characteristics of these processes are described using empirical data collected from many operating facilities. Additionally, the major aspects of the health physics and radiation protection programs that were developed at these first generation facilities are discussed and contrasted to circumstances of the current generation and state of the art of uranium ISR technologies and facilities.

INTRODUCTION

Much interest has again developed in alternative, i.e. non conventional methods of uranium extraction in recent years. Ore grades considerably below the economic demands of conventional techniques, i.e. underground and open pit mining, have become attractive. This is due primarily to the lower capital expenditure requirements, reduced manpower intensiveness and less environmental impact of these non-conventional methods. Uranium solution mining, or in situ recovery, has received considerable attention and financial commitment from major international mining companies as well as the large number of “Juniors”, i.e., companies established in recent years to pursue uranium development projects. Production facilities generating poundage from alternative uranium recovery technologies have operated in the U.S. since the late 1960s, using ore-grade feed to milling processes as low as 6–8 ppm uranium [1, 23] (Wyoming Mineral Corporation, 1977). The majority of historical solution mining interest in the U.S. has been associated with uranium roll fronts in South Texas, Wyoming, Eastern Colorado and associated with historical conventional uranium mining areas in New Mexico and Wyoming. The common denominator of many of these geologic settings is that the ore has been deposited by contact with reducing geochemical environments in shallow fluvial sandstone formations, confined by non-porous shale or mudstone layers above and below the uranium-bearing units.

STUDY POPULATION

The solution mining facilities from which operating data is presented in this paper used alkaline leach chemistries and bicarbonate as the complexing agent during the period of study (1975–1982). Development and progression of these facilities proceeded in a step-by-step fashion as a general function of wellfield size and corresponding processing plant equipment capacities and flow rates. Initial circulation of lixiviant for assessing general geochemical characteristics of the ore body usually began with 5–10 wells and a processing flow rate of approx. 100 liters/min ("test” plant). In some cases, an intermediate stage of development was used, i.e., “research and development” plant. Typical process flows were approximately 400 l/min. with several dozen to approximately 100 wells. The final stage of development was the commercial scale production facility with process flows in the range of 5000-12 000 1/min. and associated wellfields of several dozen acres ("production" plant). Table 1 presents the number and associated operational years of each developmental stage from which radiological monitoring data was accrued and incorporated for this paper.

TABLE 1. STUDY POPULATION

Plant development Stage	**Number of Facilities**	**Total Study Years***
Test	4	4
R&D	2	3.5
Production	3	8

* Sum of operational years under study for each facility in that development stage

PROCESS COMPONENTS

The solution-mining process consists of five major operational components: (1) ore body; (2) wellfield; (3) lixiviant; (4) uranium recovery process; and (5) waste impoundment facilities and associated waste management strategies.

Ore body

Uranium deposits typically amenable to solution mining are usually associated with relatively shallow aquifers, about 30–150 meters sub subsurface, confined by non porous shale or mudstone layers. Uranium was transported to the present locations over geologic time as soluble anionic complexes by the natural movement of oxygenated groundwater.

Uranium deposition occurred in areas where the groundwater conditions changed from oxidizing to reducing. This produced a roll front deposit with uranium concentrated at the interface between the oxidized and reduced sandstones. This interface is commonly known as the Redox Interface. A vertical cross section of a typical uranium roll-front deposit showing the basic solution mining approach to uranium recovery is depicted in Figure 1.

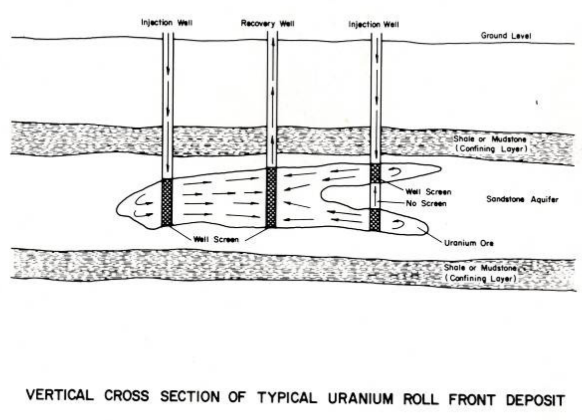

FIG.1 Basic solution mining approach.

Wellfield

The wellfield provides the means by which leach solution, known as the lixiviant, is circulated through the ore body to recover uranium. Therefore, the wellfield design is crucial in maximizing the effectiveness of lixiviant confinement and utilization. The principal considerations are well spacing, injection/production well orientations and well completion methods. Well spacing and orientation is influenced by the hydrologic characteristics of the formation which limit the rate and efficiency of lixiviant circulation. Well–completion techniques contribute to vertical confinement and vertical sweep efficiency of the lixiviant through the mineralized zone. The ultimate number of injection and recovery wells comprising a wellfield is established by the desired rate of mining and the geohydrologic characteristics of the aquifer, in conjunction with the well patterns.

Lixiviant

The lixiviant reverses the chemical conditions which led to uranium deposition and thus solubilizes uranium as it is circulated through the mineralized formation. It consists of groundwater fortified with an oxidant and an anionic complexing agent. The oxidant converts uranium from the +4 (reduced) to the +6 (oxidized) valence state, making it amenable to complexation and solubilization. In these alkaline leach solution mining projects, the lixiviant composition was 0.25–1.0 g/l H_20_2 and 1.0–5.0 g/l HCO_3 at a slightly alkaline pH. Gaseous oxygen was also used in lieu of H_20_2 as the oxidizing agent. An example of the basic mobilization chemistry in situ associated with these facilities is presented below. Other lixiviant chemistries were also investigated at that time involving, e.g. sodium / magnesium carbonates and acid leach methods. In the current generation of ISR facilities, the preferred complexing agents are gaseous oxygen with carbon dioxide or sodium carbonate (see below).

Alkaline leach based facilities:

Oxidation: $U^{+4}O_2 + H_2O_2 > U^{+6}O_3 + H_2O$

Leaching: UO_3+$(NH_4)_2CO_3$+H_2O>$(NH_4)_2UO_2$ (CO_3)+H_2O_2
Current Generation of ISL/ISR:
Oxidation: $U^{+4}O_2$ +O_2 (gaseous) > $U^{+6}O_3$
Leaching: UO_3 +$X(HCO_3)_2$>$XUO_2(CO_3)_2$+H_2O
(where X is any monovalent or divalent cation)

These uranium-recovery processes consisted of four basic process circuits: (1) lixiviant/sorption circuit; (2) resin transfer circuit; (3) elution/precipitation circuit; and (4) product drying and packaging (Figures 2 and 3).

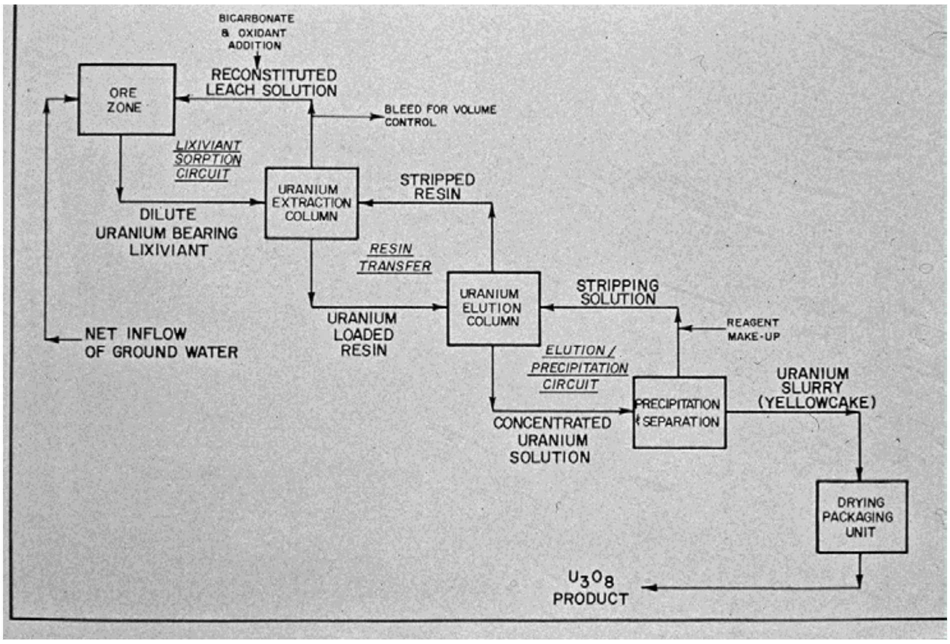

FIG.2. Process flow diagram.

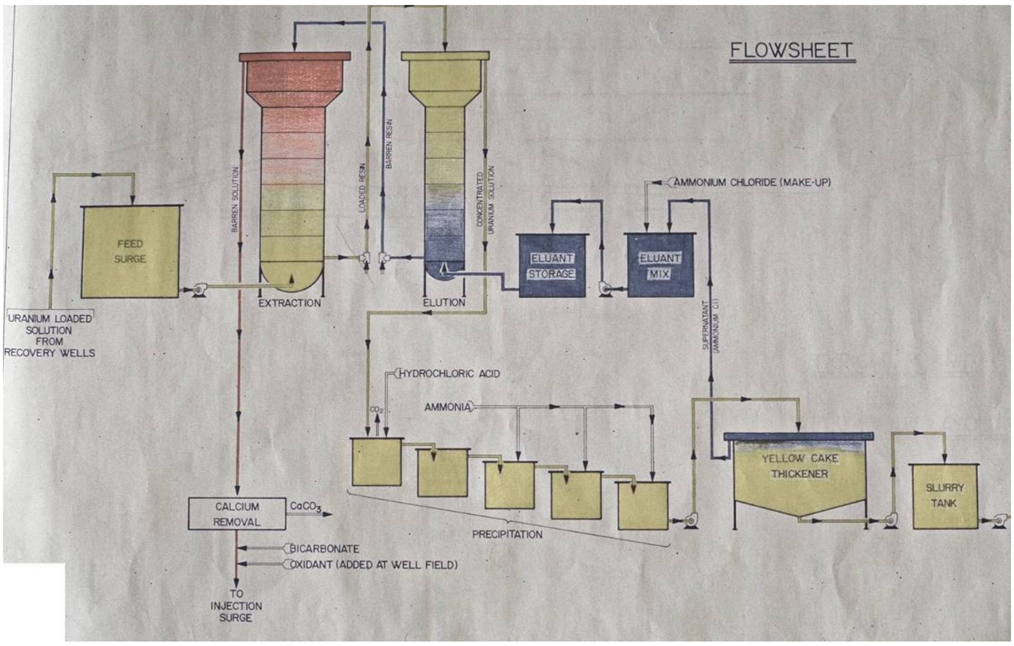

FIG. 3. Process schematic.

In the lixiviant/sorption circuit, uranium is extracted from the recovered lixiviant by adsorption onto anionic resin. The lixiviant is then refortified and reinjected into the mineralized formation. Some provision for calcium control may also need to be incorporated to reduce calcium carbonate precipitation in the fortified lixiviant which, if not removed, could plug up the wells and reduce formation permeability. The degree of calcite precipitation is site-specific and is related to the geological formation and lixiviant chemistry chosen. More will be said about this calcite byproduct later.

The lixiviant/sorption circuit and the elution/precipitation circuits of these facilities were interconnected by means of a resin transfer system only. In the elution / precipitation circuit uranium is chemically stripped from the resin and precipitated from solution (typical concentrations in the pregnant eluant are 8–20 grams/litre uranium [2; 20]. In current designs, the resin may be eluted directly in the ion exchange vessel, or as was the case with these facilities, transferred to a separate elution column or tank. The uranium precipitate, ammonium diuranate or uranyl peroxide, depending on the precipitation chemistry, may then be conveyed to a product drying/packaging facility where it is converted to the final UO_3/U_3O_8 product. The barren supernate is refortified and recycled through the elution/precipitation circuit.

Currently, some process strategies involve a “final product” of loaded resin or an intermediate precipitate only, and then shipping this product to another facility for further processing. The final product may therefore be loaded resin, an intermediate product or slurry, rather than a $U0_3/U_3O_8/UO_2$ powder [3; 5].

Waste impoundment and management

Various amounts of liquid and/or solid wastes may be generated by these processes. Potentially large volumes of liquid waste may need to be impounded resultant from over recovery in the wellfield and for process chemistry control. Over recovery, i.e. recovery of several percent greater volume than is re-injected into the formation, is typically necessary to maintain a net inward movement of groundwater into the mineralized zone for solution control in situ. This results in continuous liquid bleeds from the process which were impounded at the surface in large holding ponds. Surface impoundments were typically equipped with high density polyethylene (HDPE) liners, depth gauges and underground leak-detection systems. The radiological character of the impounded liquid wastes is site specific but typically includes small amounts of residual Uranium and radium 226 concentrations on the order of 20—110Bq/l. Volumes were controlled via enhanced evaporation techniques, e.g. brine concentrators. Ultimate disposition of these fluids involved chemical treatment, e.g. reverse osmosis, to reduce parameters to near baseline values and re - injection during site restoration and decommissioning activities. Currently, an alternative method for disposition of these fluids is the use of deep well disposal into an aquifer that has been previously determined by regulators as unsuitable for domestic use.

Some facilities also generated a solid waste which was removed from the process and similarly impounded at the surface. Depending on site-specific formation characteristics and lixiviant chemistries, variable amounts of a calcite ($CaCO_3$) precipitate was formed in the process. The degree of precipitation was site specific and related to the local importance of calcium chemistry and choices of pH control if any. As mobilized radium will follow the calcium chemistry in the process, this by-product, if important at a particular site, will invariably contain the majority of mobilized radium 226 byproduct material as radium carbonates and sulfates, coprecipitated with the calcium carbonates. Depending on site and process specifics, these precipitates may need to be removed from the process to prevent well plugging and reduction in formation permeability. They were typically impounded at the surface in ponds similar to the liquid waste evaporation ponds, in tanks, or drummed as produced. Although the specific activity (Bq/g) of this material is typically less than conventional mill tailings, and is almost exclusively uranium and radium 226, nonetheless the material must be considered as byproduct material and requires disposition as such. In the facilities studied, the radiological character of this material typically involved several hundred ppm uranium and 10-110 Bq/g radium 226.

RADIONUCLIDE MOBILIZATION

A relatively small portion of the uranium daughter products in the ore body are actually mobilized by the lixiviant. The vast majority of secular equilibrium radionuclides remain in the host formation. Table 2 presents typical concentration ranges for the facilities studied in the processing plant feed stream as well as the refortified tails being returned to the ore body. However, it should be noted that such values are probably process specific and may also be facility age dependent. It appears that the thorium 230 will equilibrate and very little is actually removed by the process. The majority of the mobilized radium 226 (80–90%) which is 5~15% of the calculated equilibrium radium in the host formation, follows the calcium chemistry in the process and resulted in radium carbonates/sulfates in the calcite slurry bleed stream.

TABLE 2. RADIONUCLIDE CONCENTRATIONS IN PROCESS STREAMS (BQ/L)

	Th 230	Ra 226	Pb 210
Pregnant Lixiviant (returning from underground)	56-93	10 - 150	<1
Barren Lixiviant (being reinjected)	48 -81	1.9 - 4.4	<1

It appears that little, if any lead 210 is mobilized as the lead Carbonate complexes formed in situ are virtually insoluble in the alkaline lixiviant processes studied. In addition to the species just discussed, variable amounts of radon 222 gas are brought up from underground dissolved in the lixiviant. This subject will be treated in some detail in a later section of this paper.

RADIOLOGICAL CONSIDERATIONS

The radiological circumstances, controls and monitoring requirements of uranium solution mining processes are associated with four broad categories:

(1) Hydrologic/groundwater controls and monitoring of solution flow patterns underground;
(2) General environmental impact assessment and monitoring;
(3) Special considerations for radon evolution mechanisms; and
(4) Operational health physics and radiation protection programs.

HYDROLOGIC/GROUNDWATER CONTROLS AND MONITORING

The geologic siting of the ore body, i.e. relatively permeable sandstone confined by shale or mudstone and the subsequent control of groundwater movement are basic to the mining operations and to environmental impact management and control. ınjection and recovery well flows must be balanced so that chemical solutions do not migrate out of the mining zone resulting in excursion conditions. As has been previously discussed, the radiological character of the solution returning from underground is composed of low-level concentrations of radioactive species. The average uranium concentration is typically less than 0.1 weight percent (1000 ppm). Environmentally speaking, the need to control migration is as much a chemical control need as a radiological one.

To detect solutions that have potentially migrated out of the mining zone, monitor wells must be placed in the geologic unit being mined and in other geologic units that must be protected. These wells, encircling the wellfield within 100–200 meters of the mining unit, are used to detect potential migrations from the wellfield so that expedient detection and corrective actions can be taken to draw back the lixiviant into the mining unit. Additionally, trend wells are often drilled into the mining zone between the monitor wells and the mining unit. Trend wells are used to monitor solution and water table levels and detect potential migrations earlier. Should upper and/or lower aquifers exist that need to be protected, monitor wells are drilled into the first aquifer above and/or below the mining unit.

GENERAL ENVIRONMENTAL IMPACT ASSESSMENT AND MONITORING

The monitoring programs required to quantify effluents and environmental impact at these solution mining facilities were typical of the environmental requirements for conventional mills and were consistent with the requirements of U.S.NRC Regulatory Guide 4.14 [22, 4](U.S. Nuclear Regulatory Commission, 1980b) and/or applicable state regulations and the conditions of the facility's radioactive material license. Typical considerations in this regard included:

- Radon releases from evaporation and surge ponds / tanks, top of ion exchange columns, in plant tank local exhaust system release points, etc;
- Radionuclide particulates in air at site-boundary locations, specifically for uranium (natural), thorium 230, radium 226 and lead 210 (particularly if drying/calcining steps are involved), and passive monitoring for radon 222;
- Isokinetic type sampling of dryer/calciner scrubber exhaust and other particulate point source release locations;
- Soil, vegetation, food crops in site environs for same species as for air particulates.
- Radon sampling at site boundary locations;
- Offsite sampling of surface and groundwater potentially impacted by site activities;
- Direct radiation measurements at site boundary locations.

Note that several technical advances in recent designs are expected to reduce both the radon and radionuclide particulate emissions relative to the observations and measurements made at these first generation ISL/ISR facilities. Specifically, current designs tend toward (1) use of "enclosed systems" in the recovery and ion exchange process steps thereby reducing opportunities for points of radon release and (2) use of vacuum dryers (rather than higher temperature calciners) with little, if any expected particulate emissions. See discussion on improvements in modern designs below

SPECIAL CONSIDERATIONS FOR RADON EVOLUTION MECHANISMS

A great deal of information has been published over the years on radon gas and its daughter products associated with occupational exposure in underground mines and potential environmental impacts from surface tailings impoundments. In solution mining processes, although the characters are the same, the relative roles they play can be different. It appears that the majority of radon which is released at the surface is not, as at a conventional mill, a result of on-surface decay of radium over time. The radon is brought to the surface dynamically, dissolved in the lixiviant returning from underground. Just as dynamically, that portion of the total dissolved Radon which is above the solution's saturation value, is released when encountering atmospheric pressures and temperatures. The fact that the vast majority of Radon released results from dynamic plant operation rather than from surface impoundments was quantified and verified in [22, 4], (U.S. Nuclear Regulatory Commission, 1980b).

Although radon is considered minimally soluble in water at standard conditions, the physical and geochemical environments in situ apparently enhance the amount of gas the fluids can carry by several orders of magnitude. An empirical model was developed to measure the Radon release rate and was applied to a commercial in situ leach facility [4, 5]. Data for this facility indicated a source term of 10^{12}–10^{13} Bq/yr at an average recovery flow rate of 3000 l/min. This parameter may be site-specific and is probably related to ore grade, formation characteristics and other factors. On a Bq released per kg U_3O_8 recovered basis, this is approximately 50 percent of the model mill case described in the U.S.NRC Generic Environmental Impact Statement (GEIS) for uranium milling [6, 17]. Table 3 presents radon and radium values as measured in various process components. The gas will evolve from solution in the early stages of the process as it becomes exposed to the surface environment. Depending on the limitations at a site, points of evolution could involve evaporation/surge ponds, in-plant surge tanks and tops of absorption columns, or combinations thereof. Monitoring is therefore necessary for environmental impact assessment, to define appropriate engineering controls (local exhaust systems e.g.), to assess occupational exposure conditions and to verify that exposures are maintained as low as is reasonably achievable [21, 7], (U.S. Nuclear Regulatory Commission, 2002).

TABLE 3. TYPICAL RADIUM AND RADON CONCENTRATIONS IN PROCESS

Process stage/ Location	**Ra 226 ***	**Rn 222***
Circulating lixiviant	3 - 20	300 - 7000
Calcite in clarifiers	30 - 100**	N/A
Evaporation ponds in solution	20 - 30	Equilibrium assumed
Evaporation ponds, sludge	30 - 45	Equilibrium assumed

*Bq/l except ** which is in Bq/g $CaCO_3$

OPERATIONAL HEALTH PHYSICS AND RADIATION PROTECTION PROGRAMS

Numerous historical assessments appear in the literature which describe the health physics monitoring and radiation protection programs associated with conventional uranium mining and milling [8, 9, 10, 11, 12]. The radiation protection program requirements at a ISR facility are very similar and, in many cases, identical to those of a conventional mill [13]:

- airborne monitoring for long lived alpha emitters (U, Th) in appropriate process areas, primarily drying/calcining and packaging areas including combinations of grab sampling, breathing zone sampling and continuous monitoring techniques;
- surface area contamination surveillance and control throughout plant areas
- respiratory protection programs if necessary
- bio-assay (urinalysis) programs appropriate for the uranium products to which employees are potentially exposed (product specific solubility characteristics can have metabolic implications for bioassay [3, 14, 15, 16]
- work control and training via formalized procedures
- internal audit and quality control programs to ensure execution of safe work practices and regulatory compliance

— radon/daughter monitoring, particularly at front end of process where radon is most likely to evolve from solutions returning from underground
— external exposure monitoring primarily in areas in which large quantities of uranium concentrates (ADU, uranyl peroxide, U_3O_8) are processed, packaged and/or stored. Additionally however, at the facilities comprising the study population of this paper, radium 226 build–up occurred in resin columns, sand filters and clarifiers, etc., resulting in requirements for control and monitoring of external beta / gamma exposure during the maintenance of these systems.

Frequencies and details of program implementation are, of course, a function of applicable regulatory requirements, process specifics and necessary good health-physics practices (e.g., [17, 18]). For example, at some of the ISL facilities being developed today, the process will truncate at resin loading or at an intermediate precipitate with further processing to take place at another facility elsewhere. Accordingly, the radiation protection program should be comensurate with the degree of radiological hazard specific for the facility design and operational strategies.

As described previously, solubilized radon will be brought up dynamically from underground with the uranium bearing solutions. A portion of the dissolved gas may be released within the first few process areas, primarily surge ponds and tanks and/or at the tops of the absorption columns themselves. In the case of facilities in the warm southern U.S. out-of-doors (e.g. Texas), large surface area surge ponds were used and therefore very little gas remained in solution by the time the pregnant lixiviant reached in plant areas. On the other hand, severe Wyoming winters in the northern U.S. prohibited exposure of the solutions to the atmosphere out-of-doors and were piped directly from enclosed wellfield valve stations and surge tanks to in plant recovery tanks. Local exhaust systems were required to remove the gas from in-plant vessels before it became an occupational exposure concern. Monitoring may therefore be required to evaluate engineering and health-physics needs within general plant areas, and particularly prior to entrance into enclosed areas and tanks which can be subject to significant radon daughter build–up. It should also be noted however, and as previously discussed, current designs tend toward use of enclosed systems for lixiviant recovery and ion exchange. Accordingly, less opportunity should be available for points of radon release, either into the environment or within plant work areas.

In any individual facility the level of effort required to assess and control radon and daughter exposure conditions, both in terms of monitoring frequencies and ventilation needs, must be evaluated on a site–specific basis and can change within a facility as design or operational conditions change. The mechanics of radon solubilization in situ may involve a complex combination of factors including the geochemical characteristics of the ore body, lithographic texture of the sandstone, depth of, temperature and pressure in the ore zone, as well as the details of the lixiviant chemistry itself.

To summarize the radon/daughter occupational exposure circumstances at these facilities, the following observations were made. Under differing circumstances and conditions, both radon gas as well as its short lived daughter products (Po^{218},Pb^{214}, Bi^{214}, Po^{214}) can be important concerns in occupational health physics programs. A great deal of information exists in the literature confirming that the daughters of radon are considerably more important than the radon parent in contributing to respiratory track dose [19, 20, 21, 22, 23]. Extensive radon and radon daughter monitoring at these ISL facilities indicated that severe disequilibrium can be encountered between radon and its daughters at both ends of the continuum. Situations were observed in which significant concentrations of Radon gas as high as 10^3–10^4 Bq/liter in air) in the absence of significant levels of Radon daughters were measured in general plant areas. Conversely, situations were identified (e.g. within enclosed, poorly ventilated areas, tanks, etc) in which several tens of working-level concentrations of radon daughters were measured in the absence of comensurate levels of radon gas. Ventilation conditions obviously play a large role in determining this relationship. Monitoring considerations, particularly during startup phases and when operating conditions change, should include both the measurement of radon daughters (for accurate assessment of potential dose commitments) as well as for radon gas to adequately identify potential sources so that necessary engineering controls can be implemented.

IMPROVEMENTS IN MODERN DESIGNS

Modern ISR designs are expected to reduce radiological emissions and potential for employee exposure relative to first generation ISR facilities due to several important advancements:

- Tendency toward enclosed systems at front end (lixiviant circulation, resin loading and elution) providing less opportunity for radon gas release;
- Use of vacuum dryers rather than calciners should reduce effluent releases of yellowcake product to insignificant levels;
- The lower operating temperature of vacuum dryers relative to calciners is expected to produce a more soluble final uranium product (more UO_3, less U_3O_8 in mixture) with less potential for longer term pulmonary retention and resultant dose. However, chemotoxicity must be considered;
- Less concern or need for pH control of lixiviant relative to first generation alkaline leach processes. This should reduce the importance of calcium and radium chemistry and therefore less radium should be mobilized from the host formation.

CONCLUSIONS

Special considerations are dictated by the in situ recovery technology related to hydrologic control of solutions underground and the management of large volumes of liquid at the surface. Some unique radiological aspects of ISRs result from the characteristics of Radon solubility in–situ and resultant gas evolution mechanisms at the surface.

Conventional mill tailings are not generated by the ISR technology. However, solid LLW (“byproduct materials”) can result, primarily from process specific aspects of Radium chemistry and mobilization

Health Physics and radiation protection programs required for ISRs are similar to conventional mills as well as any uranium facility processing and manufacturing industrial U compounds with natural U enrichment. However, the degree of robustness and specifics should be dictated by individual facility designs.

SUMMARY

This paper has presented an overview of in situ uranium recovery processes and associated major radiological aspects and monitoring considerations. Admittedly, the purpose was to present an overview of those special health physics considerations dictated by the in situ uranium recovery technology, to point out similarities and differences to conventional mill programs and to contrast these alkaline leach facilities to modern day ISR designs. As evidenced by the large number of ISR projects currently under development in the U.S. and worldwide, non conventional uranium recovery techniques, such as ISL/ISR (solution mining), can play a significant role in complimenting uranium supplies during the next decade.

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LONG TERM ENVIRONMENTAL STEWARDSHIP

R. Edge
U.S. Department of Energy, Albuquerque, New Mexico, United States of America

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INTRODUCTION

The intent of this paper is to discuss Long Term Environmental Stewardship (LTS) primarily as it relates to uranium mill tailings disposal facilities and more specifically to the US Department of Energy's Uranium Mill Tailings Remedial Action Project (UMTRAP). The first portion of the paper discusses why and how to plan for LTS activities. The second portion of the paper describes what those LTS activities may consist of. The last portion of the paper discusses some observations and lessons learned over time on the UMTRA LTSM Program.

WHY LONG TERM ENVIRONMENTAL STEWARDSHIP?

At many remediated sites there are some residual hazards or post remediation activities that are necessary to ensure protection of the public and the environment. These may be due to technological limitations, limited continual operational activities, economic limitations, worker health and safety considerations, necessity to monitor future land use or surveillance and maintenance activities necessary to confirm performance requirements of disposal facilities. Remediation decision makers, with approval from regulators and input from the stakeholders, may have agreed upon cleanup criteria or remedial actions that, in many cases, will result in leaving some residual hazards [1]. These residual hazards will most likely include material in disposal units, and residual contamination both in remaining facilities, and in various media, such as groundwater, surface water, and soil. In some cases cleanup remedies may not reduce contaminant levels to concentrations considered safe for unrestricted use. In other cases these wastes and residual contamination will pose hazards far longer than the design life of the measures implemented to contain them. These situations result in the necessity of post-remediation activities. In order to ensure protectiveness, in light of uncertainties associated with future events and conditions that cannot be foreseen at the present, sites must be managed to prevent future exposure pathways (i.e., maintain and monitor physical and institutional controls over the time period necessary). Final or interim decisions include obligations to conduct activities that will provide assurance that the remedies are remaining protective [1]. In the U.S. these activities are called long term stewardship (LTS) or post closure care. It is the role of long term stewardship to ensure that the requisite management takes place, and future site operators, regulators, and interested members of the public have access to the information necessary for them to evaluate the consequences of events and necessary changes over time. On the US Uranium Mill Tailings Remedial Action Project (UMTRA), this was accomplished through the implementation of the Long Term Surveillance and Maintenance Program (LTSM). A critical element of the success of an LTSM Program is the development of a Long term Surveillance and Maintenance Plan (LTSP).

WHY DEVELOP LONG TERM SURVEILLANCE PLANS?

As described in the introduction, at many sites/facilities where environmental cleanups have occurred there is a need for systems and activities to ensure protectiveness long after the remediation. On UMTRA, there was a need to conduct groundwater monitoring activities and to ensure the disposal cells were functioning as planned. The LTSP was a mechanism to develop a well organized approach to these activities. LTSPs are valuable for a number of reasons [1]. The most obvious reason is that they may be required by law or regulation as in the case of UMTRA. In addition, LTSPs may serve to:

- improve management both before and after cleanup is complete (begin with the end-state in mind);
- facilitate development of a baseline scope, schedule and cost for LTS;
- provide a mechanism for demonstrating accountability to the public by clearly communicating the defined end state, maintenance requirements, performance metrics, monitoring programs, and contingencies in place to address the impact of changes to the end state (e.g., decisions made to change land use or unexpected maintenance issues or deviations from predictive modelling due to reliance on assumed values for uncertain factors that prove to have been in error);
- encourage strategic planning and identification of cost savings and optimization;
- provide a mechanism to identify technology needs by which future technological advances will be reviewed and implemented, as appropriate;
- serve as a single, consolidated reference point for knowledge management for future managers/owners of the site or facility; and
- present an opportunity to integrate and coordinate under one "umbrella" all required post-cleanup elements, such as five-year reviews (as required under environmental law in the U.S.), or site-specific post-closure permit requirements, state-specific closure requirements, long term monitoring plans, exit strategies," land use controls, air monitoring systems, license requirements, agreed-upon local requirements, and requirements detailed in other relevant agreements.

The development and implementation of LTSP’s will also facilitate discussion between the operator or owner of the site, local regulators, community officials, and other interested members of the public in determining key components of the post-remediation planning and determining how these activities will be managed at the sites.

The U.S. Department of Energy’s Grand Junction Office develops long-term Surveillance and Monitoring (LTSM) plans as part of the requirement for sites (former uranium milling facilities) governed by the Uranium Mill Tailings Radiation Control Act (UMTRCA) as mentioned previously. In addition, as early as 1998, in recognizing the benefits of post-remediation planning, the Environmental Management Advisory Board, an advisory group to the U.S. Department of Energy (DOE), formalized recommendations for site-specific long term surveillance (LTSM) plans as a means to better manage LTSM at sites. LTSM plans are now required for all DOE sites, or portions of sites, where DOE anticipates LTSM obligations.

WHEN SHOULD POST-REMEDIATION PLANNING BE INITIATED?

Ideally, post-remediation considerations should be integrated during planning and implementation of all cleanup projects. At a minimum, LTS activities should be evaluated as part of the life-cycle cost analysis for environmental remediation projects .Regardless of what entity will ultimately be responsible for LTS, there is a clear need to document decisions, assumptions, the final end state of the site, and the activities necessary to maintain that end state. These items need to be agreed upon and documented by the key decision makers prior to site (or portion of site) closure so that future operators, regulators and interested members of the public have the information necessary to make decisions as changes in site conditions take place [1].

WHAT ARE POST-REMEDIATION ACTIVITIES?

For the purposes of this document, they are defined as the set of activities necessary to protect human health and the environment from physical hazards and hazards posed by residual contamination and/or wastes remaining at sites (or portions of sites) once cleanup is complete. A site is considered to be conducting post-remediation activities once required remediation (or "cleanup"), disposal, or stabilization activities are completed or, in the case of long term remedial actions (e.g., groundwater, surface waters, sediments, and entombed facilities), the remedy is shown to be functioning properly and operating as designed. A site can transition into post-remediation activities all at once, as may be the case for site with a single disposal cell, or transition in phases according to cleanup schedules. In the case of UMTRA the surface remediation was decoupled from the groundwater remediation. The long term surveillance and maintenance activities associated with the disposal cell were initiated after regulatory acceptance of the completion report (a report that demonstrates the disposal cell was built to design requirements and provides clean up verification data.). The remediation of the groundwater may go for some time period before into the LTSM program and the LTSP is revised to reflect the additional changes. This change may be as simple as incorporation by reference of another document describing groundwater related activities. Long term stewardship activities are designed to ensure that the implemented remedies remain effective for an extended, or possibly indefinite, period of time, or until such time that the residual hazard is reduced such that the site may be released for unrestricted use and unlimited access. Long term stewardship activities include, but are not limited to: (1) site monitoring and maintenance of engineered controls (e.g. surveillance activities, inspections, ongoing pump and treat activities, cap repair, maintenance of entombed buildings or facilities, and maintenance of other engineered controls such as containment structures); (2) the application and enforcement of legal or other mechanisms (referred to as institutional controls in this document) to restrict land and water use or access; (3) information management (e.g. record-keeping and public outreach activities); (4) environmental monitoring (e.g. groundwater monitoring); (5) contingency planning for emergency response and funding in the event that remedies or controls fail [1].

Monitoring and maintenance of site physical feature

Site monitoring refers to periodic inspections that verify that engineered structures and barriers constructed to contain wastes or prevent contaminant migration and/or limit exposure to humans or the environment have not been compromised. On UMTRA, the disposal cells and other engineered structures like fences, warning signs, site monuments are examined and assessed on a periodic basis to determine if they require maintenance or repair.

Site maintenance will be required at many sites and facilities. In addition to the maintenance and repair of the structures, such as waste disposal units that require routine attention, site maintenance includes maintaining site markers, warning signs and other systems used to warn people about remaining site hazards, and ensuring that fences and other barriers are in good repair.

These activities will be required as long as wastes, contamination, or facilities at a site pose a potential current or future risk. Post remediation maintenance and monitoring mitigate deterioration of waste disposal facilities, engineered barriers and site infrastructure. These activities help ward off inadvertent and intentional disturbances that could result in human, ecological or environmental exposure to remaining site hazards [1].

Institutional controls

Institutional controls (IC's) can be defined as legal and informational mechanisms that are employed to limit human activities on or near a specific parcel of land [1]. IC's can be used at a contaminated site to prevent or limit human exposure by prohibiting particular uses of the site. For example, a site which has contaminated groundwater, perhaps being remediated through monitored natural attenuation, appropriate IC's would include those which prevented the drilling of water wells. Likewise, for those sites with residual soil contamination, IC's, which, prevented soil excavation to prevent exposure, would be appropriate [1].

IC's can generally be categorized as one of two types: government controls or proprietary controls [1]. Government controls include zoning restrictions, permit programs, well drilling restrictions and other types of restrictions generally enforced by the government. Proprietary controls are legal devices, such as deed restrictions, easements and restrictive covenants that are based upon property law and are used to restrict the use of private property. All of these mechanisms have as their goal to restrict the use of a given parcel of land. The method by which that goal is pursued and who has the authority to enforce the restrictions vary depending on the particular control implemented.

Information management system

Information management systems will be necessary to store, preserve, and communicate information about a wide range of issues associated with remaining site hazards. These systems must be capable of acquiring and integrating new information with existing stored data.

At a site-specific level, basic information should be retained and preserved about several aspects of each hazard, including its physical and chemical characteristics, how it was created and whether it has changed over time, and the measures both engineering and institutional used to contain it, monitoring results associated with these measures and other pertinent information that may be of interest to the public. At a more general level, information management systems might be expected to retain information that concerns broad issues, such as demographic and economic change in the vicinity of the hazard, regional health or environmental monitoring data,, a general institutional history might be included as well.

Information management systems must manage stored information in a manner that present and future generation will have ready access. In addition this information needs to be regularly communicated to the community. This can be accomplished through a combination of various methods such as the establishment and regular updating of a website, public meetings, periodic written reports placed in public reading rooms or on-line, on-site displays, use of mass media, newspaper, radio, television etc. [1].

Environmental monitoring

Environmental monitoring is needed to ensure that information is available to perform risk evaluations and regulatory compliance over time. By monitoring the environment near residual hazards at sites and facilities, current and future decision makers could receive early detection of detrimental environmental impacts resulting from remedy failure. With that information, they would be in a position to address the negative impacts appropriately and act to limit future incidents. Similarly, by tracking the performance of these remedies, information may be developed to improve the next generation of remedies (i.e., improved waste cap or cover design).

Contingency planning

Every post-remediation monitoring program must consider contingency planning in the event of remedy failure. Given the long-lived nature of some wastes and contaminants there exists the possibility that even the most robust containment structures and barriers may fail over time even with an active maintenance program. Given this, decision-makers associated with facilities with post-remediation monitoring activities must decide the definition of failure and the appropriate response. In addition funding mechanisms must be identified to support any corrective measures deemed necessary. In some cases, the response may be minor. For example, an exceedence in a groundwater sample from a monitoring well may result in re-sampling of the well to confirm the presence of the contaminant in the groundwater. In other cases, monitoring activities may indicate a failure in a treatment system that requires major modification or to revisit the remedy altogether. One must evaluate the probability of such a scenario and plan accordingly [1].

WHEN TO INITIATE LTS MONITORING ACTIVITIES?

Generally speaking, post–remediation monitoring begins upon the completion of the remediation. In some instances, this may be signaled by the acceptance of a specific regulatory required document. In other instances, post-remediation monitoring may be based on the initiation of a long-term corrective measure that is performance based, a pump and treat system, monitored natural attenuation or permeable reactive barrier for example. The following are some examples of regulatory-based initiation of post-remediation monitoring in the U.S.:

For CERCLA (Comprehensive Environmental Compensation and Liability Act) remedial actions, the post-remediation monitoring phase start date coincides with the date the Regional U.S.E.P.A. (United States Environmental Protection Agency) official approves in writing the Interim or Final Remedial Action Report.

For RCRA (Resource Conservation and Recovery Act) closure of hazardous waste management units, the post-remediation monitoring start date coincides with the date that closure is "certified". This is generally referred to as the post-closure period and generally involves issuance of a RCRA post-closure permit by the US.E.P.A. [1].

As mentioned earlier, for Title I and Title II UMTRCA sites, the post-remediation monitoring start date is triggered when compliance with performance or engineered barrier criteria is demonstrated to Nuclear Regulatory Commission (NRC) through the acceptance of the Completion Report and they accept a site–specific Long Term Surveillance and Maintenance Plan.

In addition to the regulatory-based initiation of post-closure monitoring, there can be performance-based initiation. For example, both soil and groundwater remedies are generally designed to meet one of three objectives: 1) source removal, 2) containment, or 3) restoration.

The threshold for when post-remediation monitoring starts differs among these objectives. Therefore, with physical controls, post-remediation monitoring begins when construction is complete and controls are demonstrated to meet design specifications. Demonstration of attainment of performance specifications must first occur as part of the remedial action. Once this has been accomplished, then the role of post-remediation monitoring is to maintain and monitor the performance of the system. With hydraulic and pneumatic barriers, for example, post remediation monitoring may begin when initial testing of pressure gradients demonstrates that the design capture zone has been established. In the case of chemical barriers, post-remediation monitoring begins when the initial monitoring indicates that desired concentration reductions are occurring [1].

WHAT IS THE CONTENT OF A LONG TERM SURVEILLANCE PLAN?

In general, with respect to post closure monitoring applies the greater the risk, or residual hazard, the more complicated the post-remediation monitoring program and the more detailed the plan will be. In most cases, a brief description of activities may be appropriate with reference to more detailed monitoring plans and information on how to obtain them. The following is a discussion of the types of information that appear in a typical UMTRA LTSP [2]. The content is based on requirements specified in the US Nuclear Regulatory Commission's Regulations (10 CFR 40.27).

Introduction to the purpose and scope of the post-remediation monitoring

This section provides a general overview of the purpose and scope of the post-remediation monitoring, the legal and regulatory basis for the activities. A legal description of the site is included and a discussion of the real estate instruments transferring the site to the DOE. The real estate records are required to be kept as part of the permanent site file.

Final disposal site conditions

This section summarizes the final disposal site conditions, as a baseline for comparison over time. The description must be detailed enough so inspectors can determine changes from the baseline conditions and evaluate whether or not these changes require maintenance or repairs.

The following is a list of information that is typically included in this section of the LTSP:

- Processing history and associated contaminants;
- Detailed description of the disposal area which describes land use, surface and groundwater use, land ownership of surrounding areas, surface features such as natural or cultural resources, subsurface conditions including groundwater characterization information;
- Disposal cell design information which describes major constructed components, cross-sections and plan view drawings of the disposal cell. A description of the cover system and the features that contribute to the performance of the cover (i.e. rock or vegetative) and any other pertinent information such as design drawings or photographs.

Long term surveillance program description

This section describes the LTSM program for the specific site. Information in this section includes inspection frequency and the scope of the inspections. The qualifications of the inspection team and inspection procedures are described. It describes environmental monitoring requirements (atmosphere, water, biological). It discusses institutional controls (property ownership, signs and fences, security) record keeping (records, record keeping requirements, reporting requirements), emergency notification information, quality assurance and health and safety requirements.

This portion of the LTSP describes the objectives of the inspections, which is to report on the conditions of the disposal cell and note any changes or modifications over time. Comparisons with baseline conditions describes in the final disposal site conditions are made and provide the basis for determining disposal cell performance and for what maintenance activities may be needed.

The qualifications and size of the inspection team are based on the particular disposal site specific characteristics such as the design, surveillance requirements and time needed to conduct the inspection. If groundwater monitoring is required you want to have that expertise on your team. If vegetative encroachment is a concern, an expert in that subject area is included on the team etc.

In preparing for an inspection the inspection team is required to review previous inspection reports, review pertinent site data such as design criteria, prior maintenance or corrective action reports and comply with any access/ notification requirements.

When conducting the inspection, the inspectors observe the condition of all permanent features, note anomalous features that may require follow-on attention (erosion, effects of burrowing animals, vandalism and intrusion of vegetation). These are recorded in field note books and incorporated into a inspection report which is subsequently provided to NRC. In order to standardize the inspections from year to year for comparative purposes an inspection checklist is utilized. Photographs are taken to provide additional documentation. A log is kept of all photographs associated with each inspection.

The environmental monitoring section of the document describes the types of monitoring (air, soil, water) the frequency of the monitoring, for water, the constituents to be monitored. Detailed monitoring and sampling plans may be incorporated by reference.

This section describes the institutional controls that are being implemented, and how it is being implemented and maintained, as part of the post-remediation monitoring program. This should include a description of other use/access restrictions required to maintain redundant protectiveness and describe the location of where these controls are in effect at the site. Institutional controls may be site- wide or only a portion of a site:

Site–wide: Identify the institutional controls that are applicable to the entire site, e.g. site–wide fences and security to the extent they are considered part of the program. Note that some activities at sites (e.g. fencing, site–wide security) are similar to institutional controls but may not be directly correlated to the need to protect human health and the environment from residual hazards that remain onsite.

Portion-specific: Identify the institutional controls that are unique and directly attributable to a specific locations or portions of the site requiring post-remediation monitoring.

This section of an LTSP describes the procedure for implementing emergency response, as required, as well as criteria for determining when something is considered an "emergency" (i.e. imminent threat to human health and the environment). It includes descriptions of site–wide emergency response activities, as well as portion specific requirements, as applicable. This section provides contact information for emergency responses.

The corrective action section of the LTSP describes the procedures for implementing corrective actions and for determining when those actions are necessary. It also describes the mechanisms for reporting that the corrective actions were implemented, the reason why the corrective action was necessary, and the action taken.

The records management portion of the LTSP section identifies the records that will be archived in the permanent site file, and include a description of the following:

- Identification of post-remediation monitoring information: Identify types of records and data critical to implementing post-remediation activities at the site. This would include historical as well as new information generated as a result of post-remediation activities. (i.e. status reports, results of inspections, environmental monitoring data, operations reports, compliance reporting, and any corrective measures under taken) .
- Storage and Archiving LTS Records: Describe how and where records will be stored, the length of time they will be stored, and for what purpose the records are being maintained.
- Public Access Systems: Identify the means by which the public will be afforded access to records and site information. Identify which of the LTS records the site anticipates will be requested by the public and which records may be made accessible.

SOME LESSONS LEARNED FROM THE UMTRA LTS EXPERIENCE

One of the goals of an LTS program should be to conduct a comparative analysis of the observations and data from inspection to inspection or year to year (depending on the frequency). Depending on what is observed it may be appropriate, utilizing the graded approach, to conduct further studies to gain a better understanding of the phenomena observed. This may allow for a more proactive approach to preventing future potential performance or compliance issues. It may well form the basis for the next generation of engineers to produce an improved design which may result in better overall performance in terms of environmental protection and lower construction and maintenance costs. The following is a brief discussion of two examples from the UMTRA LTSM programme.

Long term performance of UMTRA disposal cell covers

Plant intrusion

Early designs of UMTRA disposal cells were directed at limiting radon emanation to levels below the regulatory limit (20 piC/m^2/sec) and meeting the 1000-year longevity requirement stipulated in the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA)[6]. Early designs basically consisted of three layers: 1) a radon barrier consisting of a compacted soil layer (CSL) overlying the tailings for radon attenuation, 2) a lateral drainage layer consisting of coarse sand or gravel sandwiched between the radon barrier and the erosion protection [7], and 3) the erosion protection layer which consisted of a surface layer of durable rock (see Figure 1). The radon barriers were later advocated as low-permeability barriers once the groundwater standards were promulgated and applied to UMTRA [6].

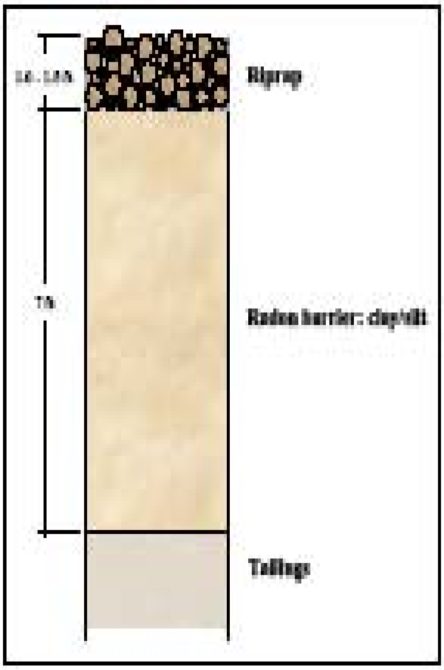

FIG.1. Early UMTRA cover design Shiprock, New Mexico.

Through the LTSM program plants were observed growing on the disposal cells within a short time period after completion of construction. As it is well known surface layers of rock reduce evaporation, increase soil water storage, and, consequently, create habitat for deep-rooted plants. Root intrusion can physically degrade covers. Macropores left by decomposing plant roots may act as channels for water and gases to bypass the soil mass in the radon barrier. Plant roots also tend to concentrate in and extract water from radon barriers high in clay, causing desiccation and cracking. Furthermore, roots can clog lateral drainage layers [8], potentially increasing percolation rates.

The DOE’s Office of Legacy Management, through the LTSM program initiated a study to determine the impact on the overall disposal cell performance [10] The primary concern being that deep-rooted plants may increase the likelihood of contaminant releases from disposal cells either through increased radon emanations through the radon barrier along root paths or through evapotranspiration and increased infiltration of precipitation through the cover. This might result in the generation of leachate in the disposal cell which would exit in the subsurface. In addition, the radon barriers were vulnerable to desiccation and cracking from wet–dry cycles, freeze–thaw cycles.

Figure 1 is an illustration of a cover constructed at Shiprock, New Mexico, in 1986, before the U.S. Environmental Protection Agency (EPA) proposed groundwater quality standards for UMTRCA sites. The Shiprock area receives an average of about 15 cm precipitation per year. The Shiprock cover consists of three layers: a 198–cm silt loam radon barrier, a 15–cm sand drainage layer overlying the radon barrier, and a 30cm layer of large, durable cobble sized rock to prevent erosion. Early laboratory tests suggested that the Shiprock radon barrier had a saturated hydraulic conductivity (K_{sat}) between 6.4 x 10^{-8} and 2.3 x 10^{-6} cm/s [9]. After groundwater standards for UMTRCA sites were promulgated, DOE became concerned that potentially deep-rooted plants observed growing on the cover, including tamarisk, rabbitbrush, and Russian thistle, could increase the permeability of the radon barrier [10].

Soil moisture monitoring and in-situ measurements of K_{sat} suggest that recharge through the cover is higher than previously thought [11]. Neutron hydroprobe measurements from June 1999 through September 2000 show that the radon barrier and upper tailings were saturated. In situ K_{sat} was measured using air-entry permeameters in pits where tamarisk, rabbitbrush, and Russian thistle rooted into the radon barrier and in adjacent pits without plant roots. Results were highly variable with a mean K_{sat} equal to 4.4 x 10^{-5} cm/s. Given saturation of the radon barrier and tailings and a higher K_{sat} than previously assumed, higher than expected recharge through the cover is likely [10].

While the study demonstrated the increase in the recharge through the cover, that does not necessarily equate to an increased public health risk. The study does show that changes in the performance of the UMTRA covers can occur over time. Having this knowledge will allow current LTSM program management the ability to evaluate the performance relative to public health, the environment, and to other alternative cover designs for use by future environmental design engineers. This example illustrates the value of a LTSM program as it all started with the observation of plant encroachment through regular LTSM inspections.

Degradation of erosion protection

The Lakeview Oregon UMTRA disposal cell was constructed in 1989. It is located in a mountainous region with wet winters and dry summers with periodic intense summer thunderstorms. The radon barrier is protected by a rock/soil matrix on top of the disposal cell and by rock erosion protection on the west facing side slope.

The erosion protection is a weathered olivine basalt. The design called for an erosion protection layer 15cm thick with a D_{50} of 2.7 inches. At the time the rock was produced from a local quarry inspectors noticed that the rock was fracturing as it was being extracted from the quarry wall. A much higher quality, densely crystalline basalt was available from a quarry 150 km from the disposal site. To contain costs and maintain the construction schedule, both of which would have been adversely affected by a 150 km haul, a decision was made to use the locally available basalt. In order to compensate for the fracturing the design criteria was changed and the thickness of the erosion protection layer was doubled to 30cm and the material was oversized to allow for some degradation.

In 1994, inspectors on the UMTRA LTSM program began to notice numerous stones were cracking, splitting or spalling as they lay in place on the side slope of the disposal cell. The rock was deteriorating under surface weathering conditions. Petrographic examination of the rock revealed it was microfractured throughout. The glassy matrix and feldspar crystals were altering to clay. The olivine is altering to iron oxides in the fractures and along the edges as well. In 1996 a procedure was implemented to measure the rock and monitor the decrease in size (Figure 2).

The design at the Lakeview site required that the D_{50} that is, 50% of the rock by weight must be larger than 7 cm. As mentioned earlier the rock was oversized to compensate for the fracturing and produced at 10 cm. Measurement of the rock in 1997 and 1998 showed the rock diameter has decreased, due to weathering, to an average of 7cm. Thus the erosion protection is near the design requirement. The function of the erosion protection is to dissipate the energy of the overland flow of water. If the erosion protection degrades below the design size, there is the potential it will erode no matter how thick the layer may be [12].

The size of the erosion protection is now borderline. It is likely that the issue will soon require attention in order to be in compliance with the design standard. This does not necessarily mean an increased risk to the public or the environment. It is important to keep in mind that the hazard associated with the uranium mill tailings is a chronic long term exposure, not an acute hazard. The most appropriate action would to be to do a pathways based risk assessment and to perform maintenance as necessary on the specific areas that need attention as appropriate.

This example again demonstrates the value of an LTSM program. Through simple inspection a changes were observed in the erosion protection of the disposal cell. Using the graded approach, a procedure was devised and implemented to monitor the rate and effects of the degradation. The procedure consisted of screen a specific area of the erosion protection and calculating by weight what portion of the rock meets or exceeds the D_{50} design criteria (Figure 2). Utilizing the data generated from this additional monitoring, thought can be given to the most appropriate path forward to propose to the regulator. A good LTSM program demonstrates due diligence and builds confidence with the public and the regulator that changes in the disposal cell/site are being identified and appropriate action are being taken.

FIG. 2. Field Testing Lakeview Erosion Protection.

SUMMARY

As can be seen there are many aspects of an LTSM program that go beyond the collection and reporting of environmental data. For the UMTRA sites the wastes left in place will remain a potential hazard for generations. The development of a detailed LTSP will facilitate cost-effective management of these sites. It will instill confidence in the pubic and the regulating authorities that the selected remedy is working, and should conditions change such that the remedies cease to work it will allow for timely detection and corrective measures to be implemented. Likewise, it will also allow for a rationale, and documentation supporting the reduction or elimination of LTSM activities. It will also facilitate a transfer of knowledge to future generations of regulators, operators and the general public for the continued protection of human health and the environment.

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SUSTAINABLE REMOVAL OF RA-226 AND U FROM MINE EFFLUENTS: A REVIEW OF FIELD WORKS IN NORTHERN SASKATCHEWAN, CANADA AND SAXONY, GERMANY

M. Kalin, G. Meinrath, M. P. Smith, W. N. Wheeler
Boojum Research Ltd., Ontario Canada

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Abstract

There is governmental regulatory interest in cleaning up uranium mine site effluents. These effluents contain uranium, radium (Ra-226), and other metals, often in excess of regulatory requirements. Chemical treatment plants need to be operated for perpetuity, and are an uneconomic, environmentally unacceptable option, as they produce radioactive secondary wastes, which require further safe disposal.

Boojum Research, during studies in uranium mine waste management areas in Ontario and Saskatchewan, Canada, found that members of the algal family of stoneworts could concentrate radium many times over ambient concentrations. Studies followed which documented the removal process of both uranium and Ra–226 from the water, the ability of these plants to concentrate both contaminants, and contaminant enrichment in the sediments under alkaline mine effluents.

This study reports on the ability of stoneworts to remove Ra–226 and uranium from uranium mine waste water. Studies were performed at two mine sites in northern Saskatchewan, one, where waste rock and mine slime sediments provide the source of contaminants at concentrations of up to 0.64 Bq L^{-1} of Ra–226 and 3.2 mg L^{-1} of uranium. The other site, a newly formed pit lake, contained lower concentrations with 0.14 Bq L^{-1} and 0.26 mg L^{-1} of Ra–226 and uranium, respectively. At these sites, bio-geochemical processes along with algae (stoneworts or phytoplankton) reduced these contaminants in the mine effluents by a factor of 10.

Wismuth (Saxony, Germany), charged with decommissioning a former uranium mining operation was also searching for sustainable treatment options. In 1998, a pilot wetland system was constructed to remove U, Ra–226, Fe and Mn from the effluents of the flooded workings of the Pöhla-Tellerhauser abandoned uranium mine. The effluent contained very high concentrations of Ra–226 (1.9 Bq L^{-1}). Pilot tests were initiated using stoneworts and baffles for biofilm formation. The transplanted biomass contained less than 1 Bq kg^{-1} Ra-226 and had accumulated 8700 Bq kg^{-1} dry weight after six months of growth in flow through test. A full scale passive treatment system was constructed treating an effluent stream of 17 $m^3 h^{-1}$ with transplanted biomass or biomass grown from oospores.

This contribution will discuss the use of these algae to remove or biopolish radionuclides in uranium mining effluents. Our objective is to create mineralizing ecosystems in mine waste management areas, which assist in and accelerate the formation of biogenic uranium and radium ore-bodies.

INTRODUCTION

The literature on passive biological treatment systems for mine waste water is extensive as reflected in recent reviews [1, 2]. Mine waste treatment systems, as reviewed, employ various flow-through systems, either subsurface or vertical flow, where plants, rooted in a substrate, remove contaminants by adsorption and absorption. In most of these systems, the changing pH/Eh regime in the root zone precipitates contaminants along with other dissolved ions (e.g. Al, Fe, HCO_3, Ca and S) as hydroxides and carbonates. This plugs the adsorption sites in the root zone of the growth substrate leading to lower hydraulic conductivity in the system, and causing the flow to 'short circuit'. Once the flow 'short circuits' the treatment becomes ineffectual. This is not an approach which is sustainable over the long term.

A more sustainable approach involves three bio-geochemical steps. In the first step, contaminants are adsorbed onto living plant biomass. As the adsorption sites fill up and the plants die, the adsorbed metals are relegated to the sediments. With anaerobic sediments present, microbes can transform the metals, with the carbon from the plants, back into minerals. This has been nature's way throughout geological time, producing many of the surficial uranium deposits around the world [3].

One of the regulatory foci on the uranium mining industry in Canada has, since the early 1980s, centred on decommissioning, with emphasis on long term environmentally acceptable solutions. This engaged the industry in a search for sustainable effluent treatment options as alternatives to chemical treatment of radium and uranium and/or as pre- or post-treatment options to supplement chemical treatment. With the Bruntdland Commission's report on sustainable development [4] additional emphasis was placed on treatment technologies with low or no waste generation associated with industrial activities.

The biogeochemical process of bio-mineralization, i.e. the formation of minerals facilitated by living matter, alters geo-environments. Schlesinger [5] in his introduction to the 2005 'Treatise on Geochemistry' goes as far as stating that 'bio-geochemistry must emerge as the critical scientific discipline that informs planetary stewardship through the rest of the century.' The geological documentation provided in 1984 by the IAEA [3] highlights the role of organic matter which is associated with surficial uranium deposits in wetland type landscapes. These conditions serve as natural analogues for uranium mine decommissioning. Much progress has been made understanding the role of microbial processes that lead to bio-mineralization and/or detoxification of radioactive elements in uranium mine effluents [6]. A sustainable, ecological approach to treatment can be derived by replicating and promoting the conditions which allow these natural processes to perform optimally in designated waste management areas and ultimately form surficial uranium deposits.

For uranium mine effluents, decommissioning measures not only need to address uranium but also Ra–226. This radionuclide is hyper-accumulated by stoneworts (Characeae; macrophytic algae). The nutrient requirements of this algal group have been studied in 1987 at the University of Toronto [7]. These algae prefer nutrient poor, alkaline water [8]. Stoneworts have no root and vascular system to transport elements from the sediment to the outside of the shoot biomass, but take their nutrients and elements from the water. They mostly form the dominant vegetation in man-made water bodies – forming extensive fast-growing underwater meadows, anchored in the sediment. Growth is from the plant tips, and decay is from the older parts near the sediment. Through this unique growth pattern they accumulate elements and contribute carbon, leading to biomineralizion in the sediment. Stoneworts form calcium carbonate and phosphate crystals on their cell surfaces and this may lead to Ra–226 hyper-accumulation.

Since 1988 the growth of stoneworts in gold tailings, Cu-Ni tailings ponds and effluents from uranium mines have been documented [9, 10, 11]. These early studies in uranium mine effluents showed that stonewort biomass contained high concentrations of radium and to a lesser extent uranium. A project was initiated to document extensively the fate of Ra–226 and uranium in a drainage basin from the Rabbit Lake uranium mine in northern Saskatchewan, operated today by CAMECO. Monitoring data covering 24 years are utilized and a summary report was submitted to the Canadian regulatory bodies [12].

This contribution compiles field data which reflect the bio-geochemical processes leading to the removal of Ra–226 and uranium from the water to the sediment. The data are partly published in the scientific literature, but to a larger extent are buried in reports. Data from an uranium pit lake which was force flooded are included along with data from Wismuth/Wisutec system were underground effluent treatment was tested [13]. Boojum Research Ltd was asked to assist in deriving scale up parameters for the full scale system. Additions to the system were needed before scale up and test data are presented.

Long term surveillance and monitoring

Link Lakes

The Link lakes are located in the Rabbit Lake drainage basin in northern Saskatchewan on the Harrison Peninsula (58’1”N.103^{o} 41”W). The peninsula is surrounded by Wollaston Lake, into which the Link Lakes drain. The epigenic deposits of uranium are poly-metallic and occur as pitchblende or coffinite [14].

The ore body is located under Rabbit Lake, at the head of the drainage basin. Rabbit Lake was dewatered and the sediments from the lake and mine slimes generated from the open pit mining discharged into Upper Link Lake above the Narrows (Figure 1). The waste rock piles resulting from the open pit mining are located above the pit and drain along with the run-off from the surrounding terrestrial basin, into a ditch, which is monitored at a station referred to as Airport Road. The effluents drain from Airport Road to Upper Link Lake. A sedimentation dam was constructed to contain the discharges during mine and pit development at the lower end of Upper Link Lake below the Narrows. Below the Sedimentation dam there is a very shallow bog/ floating wetland area which ends at the shores of Lower Link Lake. From here all surface water discharges to Wollaston Lake. Reductions in Ra–226 were observed (at monitoring stations) as the mine effluent flowed passed the Sedimentation dam, and through the shallow bog/ floating wetland area (Figure 2a). The cause of this reduction was the presence of a dense population of stoneworts which grew below the Sedimentation dam and in Lower Link Lake, but which were absent in Upper Link Lake (Figure 2b).

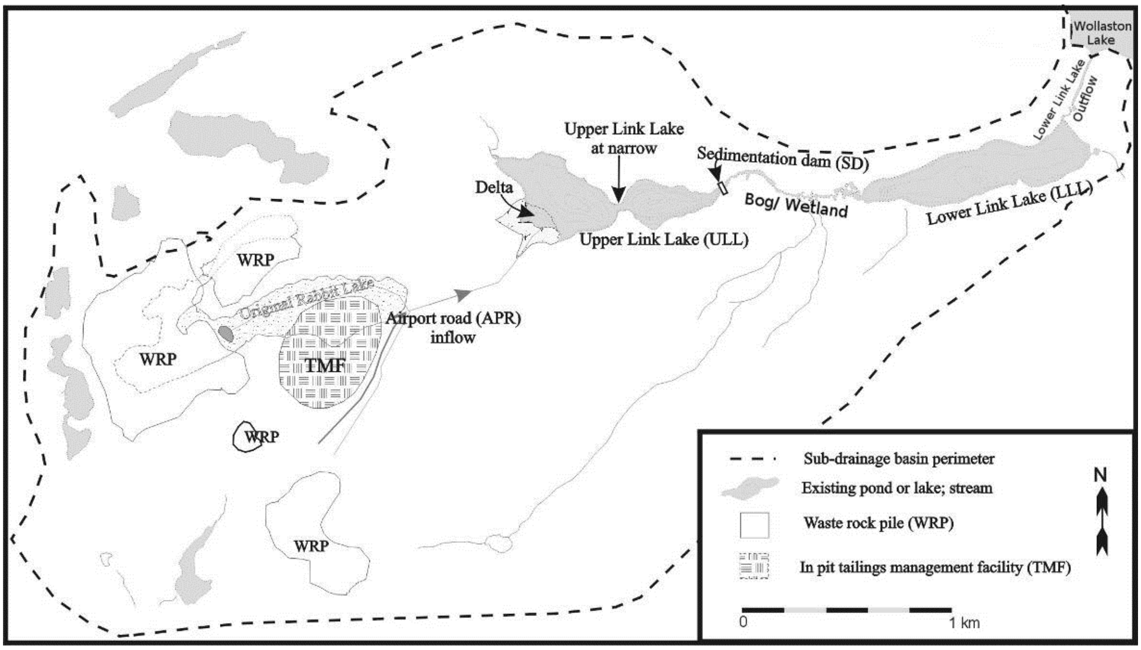


FIG.1. Link Lakes location in northern Saskatchewan.

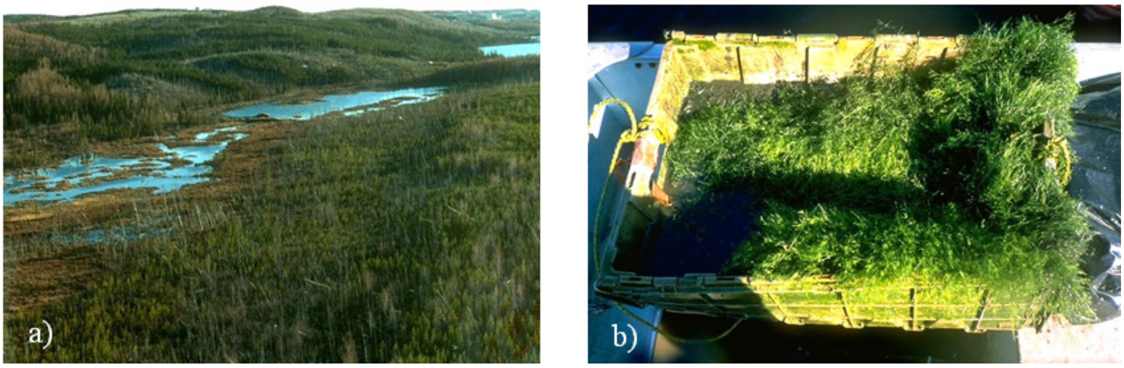


FIG.2. a) shallow bog/ floating wetland area, b) stoneworts transplanted biomass.

In an attempt to understand and utilize the characteristics of these algae, studies were initiated by Eldorado Nuclear Ltd., and continued by Cameco Corporation, the current owners. At the time, regulatory pressures existed to construct a barium sulphate treatment plant at the sedimentation dam. These were averted with the initiation of the study and the transplantation of 12 tonnes of stonewort biomass into Upper Link Lake.

The sediments and mine slimes which were deposited into Upper Link Lake from the mining operation were a major source of Ra–226 contamination. All effluents drained through the Link lakes to Wollaston Lake until the late 1990s, when the mined-out pit was converted to a tailings disposal area. This resulted in a regulatory requirement that part of the effluent be diverted to a chemical treatment plant, thus disturbing the flow to the Link lakes. This disruption affected the concentrations of both Ra–226 and uranium as it also altered the ecological system.

B-Zone Pit Lake

The B-Zone pit is another mined-out uranium ore body, located on the same peninsula, but separated from Wollaston Lake by a retaining wall. After mining finished, the pit was force-flooded. After flooding of the 5 million m^3 newly-formed pit lake changes in the water level of the lake could be accounted for by the annual atmospheric precipitation. The excess water, generated by annual precipitation needed to be diverted to a chemical treatment plant, as the concentrations of arsenic and nickel were low, but above regulatory limits. CAMECO opted to document the natural cleansing process with extremely detailed chemical and biological analysis of the evolution of a pit lake ecosystem. A complete accounting of the relegation of arsenic and nickel from the water column to the sediment was possible and the role of phytoplankton in the pit lake was correlated to water quality changes [15, 16]. Changes in the concentrations of Ra–226 and uranium in the water were also measured and are reported here, extracted from the summary report submitted to the Canadian regulatory agencies [17].

Wismuth, Germany

Uranium mining in Saxony, Germany has left a number of mines with effluents containing uranium, Ra–226, arsenic and iron. Wismuth GBH constructed a pilot test system in 1998 to treat the effluent from the underground workings of the Pöhla-Tellerhäuser mine [18, 19]. In this system, U, Ra–226, Fe, As and Mn were to be removed primarily by the actions of aquatic vegetation. The pilot test system was treating effluent at a flow between 2 and 3.5 $m^3 h^{-1}$. After three years, the monitoring data were assessed by Boojum Research Ltd. It was recommended that baffles be installed in the open water for the growth of biofilms, and that macrophytic algae (stoneworts) be tested for their ability to remove Ra–226. The biofilms and stoneworts achieved effluent cleaning benchmarks and recommendations were made to scale-up to 17 m^3 h^{-1}, the average flow from the underground workings. This system was implemented by Wisutec and started to operate in 2003 [20]. Once the system operates optimally, it will replace the existing chemical treatment facility or be placed on standby.

DATA COLLECTION

All monitoring data for the CAMECO project were collected by the environmental staff and analysed at the Saskatchewan Research Council (SRC) at their inorganic and radiochemical laboratories. The water quality monitoring data collected over two decades, along with limnological and ecological information were assembled during 12 years of study.

The samples were filtered through 0.45 µm filter paper on the day of sampling and preserved by acidification. Four litres of water were submitted to the SRC laboratory for each Ra–226 determination. Biological material was collected by Boojum Research, oven dried at 60^{o}C for 2 to 3 days to determine moisture content and wet and dry volumes. Dried biological material was homogenized in a Wiley Mill. A selected set of sediments were collected by Boojum Research utilizing an Eckman grab sampler. They were processed like the biological samples to derive the parameters needed for the calculations of sedimentation rates. The sediments were homogenized in a hand mortar and shipped to SRC in scintillation vials for analysis.

Most sediment samples in Upper and Lower Link Lake were collected by a contractor by coring and submitted to SRC as part of the State of Environment documentation. These sediments were shipped directly to SRC and dried and homogenized in the same manner. Comparability and method of sample preparation was assured by using the same laboratory over the course of the study. The results of the analysis were provided to Boojum Research and CAMECO electronically. Inconsistencies in the data submission and or analyses, when noted by Boojum, were resolved directly with SRC and reported to CAMECO.

The monitoring data for the Pöhla system were collected by the environmental staff of Wismuth/Wisutec. It is assumed that the samples were filtered 0.45 µm filter and acidified. Data were provided to Boojum Research for interpretation and are taken at face value.

DATA INTERPEPTRATION

The objective in all projects was to document and quantify the fate and behaviour of Ra-226 and uranium in the Link Lake drainage basin, the B–zone pit lake and in the pilot test system at Pöhla-Tellerhäuser. Water quality has been monitored by Eldorado and Cameco in the Rabbit Lake drainage basin since 1980, but not continuously, or with the same frequency at all stations. However, a large data set does exist for six stations monitored until 2000. This data set was statistically evaluated for outliers and validated [21] up to 2000. The last data set 2001 to 2004 was added without further statistical treatment. Field data were interpreted using a model-free classification algorithm with a high break-down, the Minimum Covariance Determinant Estimator (MCDE) [22]. The MCDE estimator has a series of favourable properties, among those, the robustness against outliers - which makes MCDE preferable over, Mahalanobis distances which are commonly used. The ellipses represent tolerance ellipses at the 95% confidence level. Thus, MCDE classifies multivariate data according to a central tendency (ellipse centre) and a scatter (indicated by the ellipse) without any preliminary user interference.

RESULTS

Link lakes

The long term data set of the Link lake system, covering the years 1985 to 2004 is used as a tool to quantify the effects of the only ecological measure taken within the basin, the transplanting, in 1989, of 12 tons of stonewort algal biomass from Lower Link Lake to Upper Link Lake. The data set was also used for the evaluation of the geochemical form of uranium at ‘Airport Road (AR)’ and ‘Sedimentation Dam (SD)’. The growth and expansion of the transplanted stonewort population into a thriving underwater meadow was monitored until 2000 and is described in detail in [12].

The major source of Ra–226 is in the mine slime sediments between the monitoring stations (AR) and (ULLN). Stoneworts were present continuously from 1980 to 2004 below the (SD), in the bog/ floating wetland. In Lower Link Lake, the population was present up to 1991, when it collapsed due to beaver dam breaks, which lead to ice scouring in the shallow areas of the lake shore. The population recovered by 1998. The final monitoring station is ‘Lower Link lake outflow (LLLO)’.

In Table 1, the average Ra–226, U and TSS concentrations are presented for three different time periods, reflecting the presence or absence of stoneworts in Upper Link Lake.

For the first period (1980–1998) stoneworts were not present in the Upper Link Lake, but the population gradually developed, affecting the lake water chemistry in the latter years of this period. Overall, the mine slimes at the delta of Upper Link Lake released an average 0.15 Bq L^{-1} to the water passing through the lake as quantified at the Narrows. This was calculated by subtracting the average concentration at the (ULLN) from the concentration present at (AR).

TABLE 1. AVERAGE TOTAL URANIUM, RADIUM AND TSS CONCENTRATION IN WATER IN THE LINK LAKES AREA

Parameter	Period of monitoring		Airport Road (AR)	Upper Link Lake at narrows (ULLN)	Sedimentation Dam (SD)	Lower Link Lake outflow (LLLO)
Ra-226 (Bq L^{-1})	pre-stonewort	1980-98	0,26 (102)	0,41 (123)	0,36 (140)	0,11 (139)
	ditch diversion, distruption	1998-00	0,34 (11)	0,64 (11)	0,27 (27)	0,06 (24)
	full growth	2001-04	0,42 (14)	0,35 (33)	0,25 (39)	0,05 (41)
U (mg L^{-1})	pre-stonewort	1980-98	3,2 (102)	1,1 (124)	1,0 (140)	0,3 (137)
	ditch diversion, distruption	1998-00	0,05 (11)	0,20 (11)	0,39 (24)	0,15 (24)
	full growth	2001-04	0,112 (14)	0,207 (33)	0,167 (39)	0,095 (41)
TSS (mg L^{-1})	pre-stonewort	1980-98	2,2 (101)	2,4 (123)	3,1 (136)	3,3 (132)
	ditch diversion, disruption	1998-00	30,9 (7)	4,9 (10)	5,4 (25)	3 (17)
	full growth	2001-04	30 (14)	2,6 (29)	5,3 (34)	2,9 (33)

Number of samples in parentheses.

Stoneworts were transplanted from Lower Link Lake to two transects above (ULLN), one at the (ULLN), and one below the (ULLN) in 1989. By 1991 only the transplanted biomass above the (ULLN) continued to grow. By 1994, the population above the (ULLN) had spread throughout the lake bottom.

In 1998, part of the effluent from the pit was diverted to a chemical treatment plant. This disrupted the flow into the Link lakes, and caused extensive phytoplankton blooms, which when the biomass died, led to low oxygen levels in the water during the winter. This, in turn, killed much of the stonewort population above the Narrows (Figure 3). Without the stoneworts to adsorb the radium, the mine slimes and likely the decaying biomass released radium (ULLN–AR=0.30 Bq L^{-1}: (Table 1)). The effect lasted approximately 2–3 years until the stonewort population had recovered. With the recovery of the stonewort populations (2001–2004), a reduction in the average Ra–226 concentration (-0.07 Bq L^{-1}) was measurable between (AR and ULLN).

Between the (ULLN) and (SD), the average Ra–226 concentrations decreased during all three time periods, suggesting that the stoneworts were removing radium. During the disturbance period (1998–2000), the TSS at (ULLN) and (SD) was high (4.9 and 5.4 mg L^{-1}) which may account for the larger reduction in radium (SD–ULLN = -0.37 Bq L^{-1}). The high TSS was probably due to the fragmenting stoneworts and decaying phytoplankton, which occurred after the effluent stream was diverted. For the other two periods, TSS was low and the radium reduction was also low (SD–ULLN=-0.05 and -0.1Bq L^{-1}). This decrease in this section of the drainage basin is due to dilution.

For Lower Link Lake the differences in average concentration between (SD) and (LLLO) are attributed to the bog/ floating wetland (Figure 2a). The recovery of the stonewort populations (1980–1998) in the Lower Link Lake resulted in a decrease in the average Ra–226 concentration (LLLO–SD=-0.25 Bq L^{-1}). During the next period, the when the population had completely recovered, the reduction was lower (LLLO–SD=-0.21BqL^{-1}). This rate continued into the third period from 2001–2004 (LLLO–SD=-0.20 BqL^{-1}).

The average uranium concentration at each station over the three time periods is a direct result of a different geochemistry. The main source of uranium is the waste rock piles north of the open pit with the tailings deposit. During the first time period, the average concentration was 3.2 mg L^{-1} (Table 1). Over the next two periods, the concentration was much lower (0.05 and 0.12 mg L^{-1}). The diversion of the flow to the treatment plant (period 2) resulted in a release of uranium from the decaying phytoplankton biomass in Upper Link Lake – hence the increase between (AR) and the ULLN) after this event. The average outflow concentration at the end of Lower Link Lake, however, did not seem to be affected much (Table 1).

Uranium concentrations do not appear to be correlated with the biomass of stoneworts, but potentially with the TSS concentrations. Uranium is associated with particulates in the water (both inorganic and organic) [23] expressed as TSS which in Upper Link Lake increase after 1998. This is possibly due to construction activities in the upper portion of the drainage basin. It may also be due to increases in the biomass of phytoplankton in Upper Link Lake, which occurred after the water diverted in 1998.

Extensive algal blooms were noted by on site staff in Upper Link Lake concurrent with the change in the flow regime (below SD: Figure 3). This may or may not be a contributing factor to the noted average increase at (ULLN), but it is also suspected that the decay of the biomass contributed to the release of uranium from the sediment. The reduction of average uranium concentrations in the undisturbed portion of the drainage basin below (SD), however, continued to be effective and the TSS values at the outflow remained the same throughout the 24 years of monitoring.

FIG.3. Sedimentation dam covered with decaying biomass at the beginning of the disturbance period.

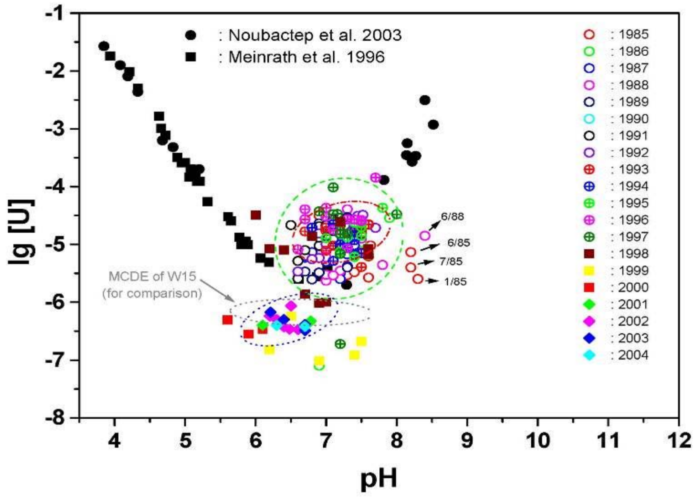
Weathering processes in the waste rock pile may have changed the geochemistry of uranium over the 24 years. To examine uranium concentrations from a purely chemical perspective, figures 4a and 4b plot each of U concentrations reported at (AR: Figure 4a with n =137) presented in pH–log[U] diagrams those for (SD: Figure 4b with n=203), each year represented by a different colour.

The solubilities of $UO_3.2H_2O$ (Schoepite) as a function of pH in equilibrium with ambient air [24] experimentally determined (black curve) are providing the frame work to assess the field data. Both data sets, the field and experimental data, have been filtered through 0.45 µm filter paper. Schoepite is the solid phase and sets at the highest solubility the upper limit for U (VI) concentrations in the absence of other agents stabilising U (VI) in solution. Details are given in Ref. [25].

As the pH changes, the maximum concentration of soluble Schoepite in the water changes through precipitation, i.e. high dissolved concentrations in the lowest and highest pH ranges. A reduction of the uranium concentration due to purely chemical precipitation has two consequences for the biological removal process. On the one hand, dissolved uranium will likely have a different surface charge than that of the Schoepite, and this could alter the ability of algae to adsorb uranium, thereby lowering the concentrations or a completely different removal process – possibly from an organic, complexed form of uranium originates from the sediments, but is not longer present as Schoepite in the latter years of the monitoring period.

The U concentrations of the Link Lake data are found scattered around or below the lower part of the Schoepite solubility curve. The ellipses surrounding the data scatter represent the result of a statistical classification procedure described above, grouping the years of the monitoring data into statistically significant different classes.

4a)



4b)

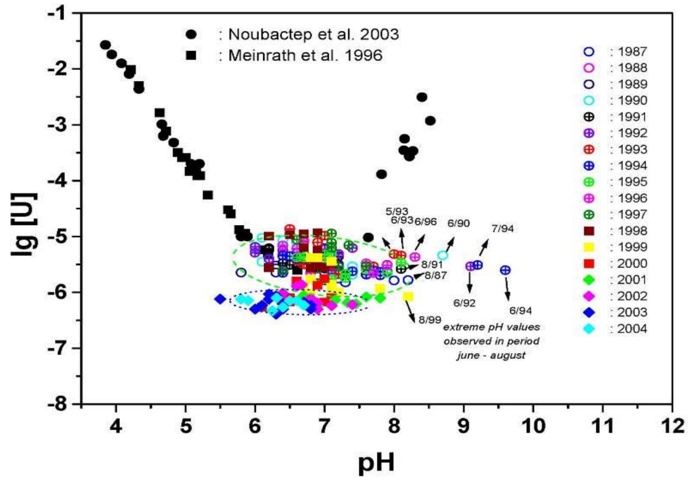


FIG.s 4a and 4b. pH vs log uranium concentrations for data from the literature and from the Link Lake system. 4a) represents data collected from the 'Airport Road (AR).4b) represents the data collected from the 'Sedimentation Dam (SD).'

The classification separates the (AR) data (Figures 4a or 4b) for the years 1985 to 1992 (open circles), but overlaps with the years up to 1997, at which point all the following years are distinctly below the range in which Shoepite could precipitate. This suggests that less uranium in the form of Schoepite originates from the waste rock pile as less surface area is available for weathering hence lower concentrations.

The comparison of the (SD) water samples, after passage through Upper Link Lake and its biological system, suggest that the uranium may be in a different form. Figure 3b shows that (SD) data clearly overlap the (AR) data up to 1997, thereafter; they fall significantly outside the Schoepite solubility range. The post-2000 concentrations are grouped and the year 1999 (yellow) forms a distinct group (ellipse not given for sake of clarity). The dotted grey ellipse is the post-2000 tolerance ellipse for the data from the (SD). This same ellipse has been transferred to Figure 4a so that direct comparisons for those years can be made. Both ellipses overlap only partly with the water at (AR) having a clear area outside of the concentrations at (SD), and they are lower (note log scale). At the (AR) increasing uranium average concentrations are noted, concurrent with higher concentration at (ULLN), and only a small reduction is noted at (SD).

The biomass in the water of Link Lakes is comprised of three components, free floating phytoplankton, attached periphyton, and the stonewort populations (Figure 5). It is difficult, if not impossible, to determine which of these three components are primarily responsible for the measured contaminant reductions. We can analyse the components for their radium and uranium content, and we can analyse the sediments, but because the ecosystems are dynamic, it would take much more extensive sampling to determine which component removed the most contaminants.

FIG.5. Submerged stonewort biomass with Periphytic Algae attached.

Some total lake surveys where biomass was quantified [12] and many observation from field staff, have provided some insight. However, concentrations of both elements in the algal biomass (Table 2) and in the uppermost 15 cm of sediments (Table 3) support the idea that it is primarily the stoneworts that are removing the contaminants. The enrichment of Ra-226 in the stonewort biomass and the sediment certainly points toward such a relationship. Overall, when biomass was high, Ra–226 concentrations from their peak to the outflow of Lower Link Lake dropped 73% during the period from 1980 to 1998, 91% from the period 1998 to 2000, and 88% from 2001 to 2004, when monitoring ceased (Table 1).

For stoneworts, the range of uranium enrichment for Upper Link Lake was 393 to 5020 µg g^{-1} and below (SD) the range had a higher maximum with 324 to 8730µg g^{-1} (Table 2). When the population died in 1998, the concentration in the biomass dropped slightly, although this may have been due to the small sample size.

The concentration range in Lower Link Lake ranged between 637 and 3430 µg g^{-1} dry weight. As a reference, one sample was collected from Wollaston Lake where a small population of stoneworts was located at 8m depth with a biomass concentration of 5.7µg g^{-1}.

The highest concentration of Ra–226 ever measured was from a stonewort sample retrieved within the bog/wetland below (SD) which contained 60Bq g^{-1}, which was closely followed with a high of 50Bq g^{-1} collected from Upper Link Lake. Clearly lower Ra–226 and uranium concentrations are evident in the biomass from Lower Link Lake.

TABLE 2. ELEMENTAL CONCENTRATION RANGE IN DIFFERENT VEGETATION BIO

Vegetation type		Upper Link Lake	Bog bellow wetland	Lower Link Lake
	Year of sampling		Range	
Nitella flexilis (stoneworts)				
U (ug g^{-1})	1988-97	393-5020 (28)	324-8730 (22)	637-3430 (19)
	1998	683-3070 (4)	2380 (1)	830-904 (2)
^{226}Ra (Bq g^{-1})	1988-97	5.0-50 (28)	1.2-60 (22)	0.6-9.5 (19)
	1998	2.5-10.0 (4)	5 (1)	1.8-2.1 (2)
*Periphytic Algae attached**				
U (ug g^{-1})	1989-91	380-1940 (12)	358-3160 (8)	Not prevailing
^{226}Ra (Bq g^{-1})	1989-91	5.5-21 (12)	1.4-42 (8)	Not prevailing
*Free-Floating Phytoplankton***				
U (ug g^{-1})	1989-91	147-344 (2)	Not analysed	Not analysed
^{226}Ra (Bq g^{-1})	1989-91	0.25-0.80 (2)	Not analysed	Not analysed

**includes Cyanobacteria and Chlorophyta ** includes Cynobacteria*

Number of samples in round brackets.

TABLE 2. [U] AND [RA-226] IN SEDIMENT COLLECTED AT 0-15CM BY VARIOUS PEOPLE FROM 1984 TO1998

Location		N	Range U(µg g^{-1})	Range Ra-226 (Bq g^{-1})
Upper Link Lake				
	Shallow - Deep Delta	7	490-3620	6-54
	Upper Link Lake - Above Narrows	27	178-4760	0.85 -54
	Upper Link Lake - Below Narrows	10	2850-8390	3.6-13
Lower link Lake				
	Wetland below sedimentation dam	6	53-753	0.12-1.87
	Lower Link Lake	8	1280-2220	1.3-2

Stoneworts are the primary vegetation source for removing radium. Uranium, however, can be adsorbed onto any plant surface. In this respect, any uranium that is concentrated by the local periphyton and phytoplankton would also benefit the removal process. Because phytoplankton and periphyton can grow rapidly, they can be major sink for uranium (Table 2). In fact, uranium concentrations are nearly the same for these other algae as for the stoneworts. For these analyses the periphyton and phytoplankton were washed free from the stoneworts and collected on filter paper. Stoneworts emerge as hyper-accumulating species. Pore water from the sediments was sampled in areas with and without vegetation and significant reductions of Ra–226 and uranium flux was quantified [26].

The concentration of uranium in the Link lake sediments was in the same range as found in the stoneworts, with the exception of the sediments below (ULLN), where the concentrations were roughly twice that of the stoneworts, and the wetland area blow (SD) where concentrations were quite low. However, even the low concentrations in the wetland are higher than concentrations of uranium found in the literature which range 0.1 to 11.2µg g^{-1} [27 - 30].

B-Zone Pit Lake

In the Link Lake system there appeared to be an indirect relationship between Ra-226 and uranium removal from the water to both stoneworts and free-floating algae (expressed as TSS). To extend the generality of this relationship, the data from the B-Zone pit lake were analysed. Here the water chemistry was monitored, after force-flooding, by determining all elements at 1 to 2 m intervals from the surface to a depth of 40 m, including nutrients [17]. The sedimentation rate or the rate at which TSS was generated was also quantified. An elemental mass balance between water, TSS (in sedimentation traps) and sediment over the 8 year period, could account for the removal of the major contaminants and elements [12 and 13]. Insufficient TSS material was available for the determination of Ra-226. Table 4 gives changes in water concentrations. In 8 years the average concentrations of Ra-226 in the 45m deep water column of the pit lake was reduced from 0.143 to 0.018Bq L^{-1}.

TABLE 3. [U] AND [RA-226] CHANGES IN B-ZONE PIT LAKE

Parameters	Concentration Range					
	1993			2001		
	Min	Max	Avg	Min	Max	Avg
Ra-226-total (Bq L^{-1})	0.03	0.2	0.143	0.01	0.03	0.018
U-total (mg L^{-1})	0.01	0.038	0.026	0.008	0.012	0.01

Wismuth/Wisutec, Germany

The surface areas established in the pilot test system and the macrophytic growth which had been established were sampled by Wisutec when the system was decommissioned and presented at a conference in Tartu 2003 [30]. In addition to Ra-226 removal by the stoneworts, also used in this passive treatment system, were the Ra-226 concentrations enter the treatment system at an average concentration of 1.9Bq L^{-1} much higher than in the Link Lake system. Here, in a small flow through experimental system the algae removed 8,700Bq kg^{-1} dry biomass in 6 months.

However, the concentrations which were reported for the biofilms were even higher than those of the stoneworts, with ranges of 11,000 to 35,000Bq kg^{-1}. In these sludge /biofilms, the iron concentrations were also very high, ranging from 107 to 397 g kg^{-1}. This does suggest, that iron hydroxide with its large surface area also adsorbs Ra226. Stoneworts are often high in iron, concentrating it from low concentrations in the water. In contrast, the above ground biomass of semi-aquatic vascular plants ranged in concentration between 50 Bq kg^{-1} to 820 Bq kg^{-1}.

DISCUSSION

The objective of these projects was to document and quantify the fate and behaviour of Ra-226 and uranium. A comprehensive data analysis provides the foundation for a decommissioning approach which integrates and promotes natural water cleansing processes and stabilization of contaminants in the sediments.

The Link Lake system essentially became a demonstration site, where the effects of natural biogeochemical processes have been documented and the ecological conditions were found to resemble those described for the formation of surficial uranium ore bodies.

The mechanisms responsible for transporting uranium from the water to the sediment are adsorption and/or integration into organic and inorganic particulates. These particulates are provided by adjacent terrestrial ecosystems, or generated in situ by local aquatic biomass. The particulates adhere to aquatic vegetation, such as the underwater meadow of stoneworts in the Link Lakes or they settle freely to the sediment as in the B-Zone Pit Lake [17]. The relationship of the phytoplankton and the Pit lake water composition is summarized in [16].

The ecological characterization (semi-aquatic with aquatic vegetation, limnological and topographical features) of the drainage basin is analogous to those documented in geological studies on the genesis of surficial uranium ore deposits, namely those of fluviatile, surficial uranium deposits. The existence of these mineral-forming (minerotrophic) conditions in the Rabbit Lake drainage basin supports the idea of natural uranium removal mechanisms. Contaminant loadings and their role in the contaminant removal process were summarized for the Upper Link Lake drainage basin [32].

This summary of Ra–226 data from passive treatment systems allows us to conclude that Ra–226 and uranium can be removed from mining waste water. The removal can be accomplished through natural, ecological processes - the growth of vegetation surfaces which have the capacity to adsorb and absorb these two elements can be influenced and managed with ecological engineering measures. The bio-geochemical removal processes that are actually taking place, although documented quite extensively for uranium (e.g. Ref. [23]) and to a lesser extent for Ra–226, are far from being understood and thus not easily influenced.

We have documented with this summary that Ra–226 and uranium are removed from water, when present in concentrations as low as 0.143Bq L^{-1} (B-Zone Pit Lake) and as high as 4.3 Bq L^{-1} (the effluent from the Pöhla–Tellerhauser underground in 2003). The removal is affected or facilitated by the ecology or growth of biota which occur in the waste water.

Further we documented that biofilms that form on organic and inorganic surfaces in these mine waste waters are just as important as stoneworts in removing Ra–226 and uranium. They provide a large surface area on which to adsorb, precipitate and transform metals. Biofilms can also collect and precipitate a number of metals, such as iron.

Clearly, there would be more support for such ecological treatment approaches in the uranium industry if these bio-geochemical removal processes were better understood, and could be better controlled and optimized. However, it can be argued if no research effort is expended, such knowledge will not be forthcoming. On the other hand, the chemical-engineering approach to treatment, as opposed to the bio-geochemical ecological approach, leaves a legacy for future generations which is unacceptable. The present practice of storing radioactive sludges in secure drums underground as practiced in Germany, and likely elsewhere, is unacceptable. With the observations presented here we hope to stimulate interest in the ecological engineering approach to the treatment of uranium mine effluents.

The ecological engineering approach relies on observations of the ecosystem existing in disturbed waste management areas. In each waste management area, differing bio-geochemical conditions, together with differing stresses on waste site ecology, force different measures to promote natural recovery. With mine site data on hydrology, botany, microbiology, geochemistry, geology and mining, along with experiments in the field, the ecological engineer can formulate a natural approach to mine waste reduction. Using bio-geochemical solutions to mine waste cleanup, we can initiate and accelerate processes which lead to the formation of future surficial uranium deposits.

The evolution of a mine site, decommissioned with ecological engineering, might look like that described in Figure 6. The goal of the ecological engineer is to assist the existing waste site ecosystems to ‘jump start’ and speed the natural recovery process, much like what takes place in Link Lake system below Sedimentation Dam. Here, floating islands (muskeg and moss) are gradually covering the area between the Link Lakes and the water is populated with stoneworts in the shallow water. In Figure 6, the floating islands are initiated on the tailings pond surface. Gradually mineral-rich sediment builds up over the tailings below. Anaerobic sediments prevent the oxidation of the tailing underneath, while together with microbes in the sediments, bio-mineralize the contaminants. The result, after a great deal of time, is the formation of surficial mineral deposits.

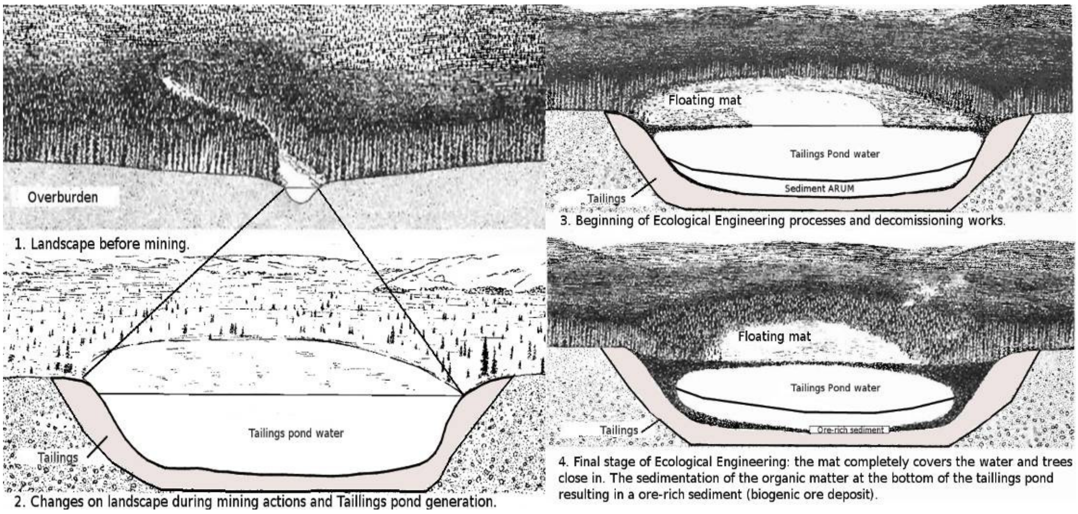


FIG.6. Evolution of a tailings pond or drainage basin with contaminated effluents mine pit and tailings when decommissioned with ecological engineering. Modified using the kettle lakes brochure from Algonquin Park [33].

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CHANGING STANDARDS AND CONTINUOUS IMPROVEMENT: A HISTORY OF URANIUM MINE REMEDIATION IN NORTHERN AUSTRALIA

P. W. Waggitt
Office of the Supervising Scientist, Darwin NT, Australia

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Abstract

Uranium has been mined in northern Australia since 1949. In the early days exhausted mines were simply abandoned. Over time community concern with environmental issues has increased to the point where minesite remediation is now mandatory. The paper reviews the changing standards that have been applied to the uranium mining industry in the north Australian region, in particular the ways in which the quality of remediation and standards of long term environmental protection have been continuously improving.

INTRODUCTION

Mine site remediation is not a new issue. Since mining first began there has been community concern about adverse environmental impacts and the state of the site once the project has been completed. The father of modern metallurgy, Agricola, drew attention to these matters in his book *De Re Metallica* in 1556 [1]. Even then there was concern that mineral resource development was at the expense of agriculture and that land would be lost to production after mining. This is perhaps the earliest reference to concerns of sustainable development. The level of concern is also affected by the nature of the mineral being mined. Whilst mining generally has some acceptance in society, albeit grudgingly, radioactive minerals, especially uranium, give rise to a whole new range of community concerns. As a result, the need for effective, lasting and safe remediation is now regarded as essential at locations where uranium has been, is being, or will be mined.

For many years minesites were simply abandoned as operations ended. There was rarely any attempt at remediation, and usually no regulatory requirement for any to be done. The modern community's attitude to environmental issues has changed. Today a new mine cannot start until all aspects of the environmental management of the operation, including remediation, have been subject to scrutiny and approval by a process that includes substantial community consultation. In effect, the community is "licensing" new operations just as much as the regulators [2].

URANIUM MINING AND REMEDIATION IN NORTHERN AUSTRALIA

Uranium mining in the Northern Territory began with the operations at Rum Jungle from 1949 until 1958 [3] followed by the mines of the South Alligator Valley (1953 to 1964) which marked the end of the "first phase' [4]. Renewed exploration activity in the late 1960s saw two new operations commence after the introduction of the Commonwealth Government's *Environment Protection (Impact of Proposals) Act* in 1974. These were Nabarlek in 1979 and Ranger in 1980. Ranger was the subject of a major environmental inquiry [5]. These mines may be considered the "second phase". Between these phases was another significant uranium mine at Mary Kathleen in Queensland. This mine operated in both "phases", from 1958 until 1963, and then again from 1976 until 1982, after EIA legislation was in force [6]. The third phase of mining is represented by the Jabiluka project, which was begun in 1998 but has not progressed beyond the initial development stage. Jabiluka has been subjected to the most stringent processes of environmental impact assessment (EIA) in Australia. All mining projects begun since 1974, the date of introduction of EIA legislation, have had to provide details of their remediation plans before being given approval to proceed.

A location map for all these sites may be found at: http://www.uic.com.au/fmine.htm.

The legislation has also been updated with the development and remediation of any uranium mine now covered as a designated nuclear activity under the Federal Government's *Environment Protection and Biodiversity Protection Act (1999)* which has replaced the former EIA legislation. This also applies to legacy site remediation.

PHASE ONE OPERATIONS

Rum Jungle

A copper mine since 1905, uranium was first identified at Rum Jungle in 1912 [7]. Following a 'new' discovery in 1949, uranium mining operated from 1954 until 1958 and copper mining continued until 1965, with the mine finally closing in 1971. The uranium was mined specifically on behalf of the Commonwealth (Federal) Government who had no obligation to rehabilitate the site, which was simply abandoned. Buildings and machinery remained on site decaying, tailings frequently washed away into the Finniss River and sulphides in the stockpiles weathered to sulphuric acid leading to releases of substantial amounts of metals and other pollutants into the Finniss River. A clean-up operation in 1977-78 was not wholly successful, achieving some revegetation, but completely ignoring the issue of acid rock drainage and the associated pollution from the waste stockpiles [7].

In 1980 due to growing public concern about the impacts on the Finniss River, by now virtually devoid of aquatic life for about 14 km downstream of the site, the Commonwealth Government agreed to fund a remediation program which was undertaken on it's behalf by the Northern Territory Government. The program ran from 1982 until 1986 at a cost of AUS$18.6M [8]. The major objectives of the program [7] were to:

- reduce the pollutants leaving the site by specific amounts (Cu by 70%, Zn by 70% and Mn by 56%);
- restrict water infiltration in waste rock piles to 5% of incident rainfall;
- to contain and reduce pollution in the water-filled open cuts;
- to reduce radiation levels to suitable levels and
- to make the area safe and to improve the site's visual appearance.

Finally, it was required that the works had a structural life of 100 years. There was no intention that the site should be rehabilitated such that the public could have unrestricted access. In the works program tailings were contained, waste rock was encapsulated in new landforms to restrict the ingress of air and water, wastewaters were treated to raise pH and remove heavy metals, and the site was revegetated. The grass species used were non-indigenous and needed fertilising and mowing to maintain the effectiveness of the cover. The result was a site quarantined from any future use and which required ongoing management for the remediation to remain effective. Such outcomes would be unacceptable today.

Whilst such an outcome was apparently acceptable in the 1980s, modern communities expect former minesites to be restored to a productive use. This became apparent when the outlying mine at Rum Jungle Creek South was rehabilitated in 1990-91. The program there required the former open cut, waste rock dump and surrounding area be rehabilitated to become a recreational lake and picnic area with unrestricted public access [9]. The significant change in community expectations over a period of less than 15 years is clearly demonstrated in the widely differing ways two sites only 5 km apart have been rehabilitated.

South Alligator Valley mining field

Thirteen small uranium mines and a mill operated in the South Alligator from 1955 to 1964 and all were abandoned when mining activities ceased. The area remained untouched until concern about public safety issues arose in the mid 1980s when the valley was included in a National Park. In 1986 tailings were removed from the millsite to a location outside the Park and processed to extract gold. Between 1990 and 1992 the Commonwealth Government undertook a program of hazard reduction works at all the minesites, including the mill. The objectives of the program were to reduce physical hazards at old workings and to reduce radiation exposure for park visitors and traditional landowners to levels compatible with the new land use [4]. The work included revegetation of disturbed areas with native species to match the surrounding vegetation. No attempt was made to fully rehabilitate the sites. In 1996 the land was the subject of a successful native title claim. As the land was handed over to the traditional owners it was immediately leased back to remain as a National Park. However, the lease required that all mine sites be fully rehabilitated by 2015. The negotiations for the design of a suitable program took several years [10]. Remediation work at the first two sites was completed in 2007 [M.Fawcett, pers.comm] and all work should be completed by 2009. A major objective of the remediation is to ensure that the sites blend in with the surrounding countryside and do not require any special management.

Mary Kathleen

From 1958 to 1963 and again from 1976 to 1982 the Mary Kathleen uranium mine operated in Queensland. After the first phase, no remediation work was undertaken, none being required by legislation at that time. However, after the second operational life ended in 1982, there were expectations from the community and requirements of the regulators that the site would be made safe. New environmental legislation had been promulgated between 1963 and 1976, and consequently the mining company had prepared a complete Environmental Impact Statement, including a remediation plan, prior to the operation’s restart in 1976. The remediation plan was updated prior to implementation in 1982 to bring it into line with the Code of Practice published by the Commonwealth Government [11]. The main objectives of the plan were: to make all areas safe for public access in terms of radiation hazards and physical risks; to remove all structures that could degrade or become hazards; to make remaining ground surfaces as erosion resistant as possible; and revegetate them with native species.

The work program, which took nearly three years to complete, included flooding the mined-out pit, covering, contouring and revegetating of the rock stockpiles, revegetating borrow pits, decommissioning and removing of the processing plant and township and revegetating those areas, and ensuring secure containment of tailings in the existing above-ground facilities. The standards of remediation were basic by today’s criteria, with limited reshaping of stockpiles and little effort to match the surrounding landforms. Concrete slabs and exotic flora are still visible in the former township areas today. Whilst the remediation outcomes were apparently satisfactory at the time, it is unlikely that the site would meet the expectations of either the community or a regulator today.

PHASE TWO OPERATIONS

Nabarlek

Nabarlek is the most recent example of uranium mine remediation in Australia. [12] The ore body was discovered in 1973 and its development was subjected to what was then considered intense scrutiny through a Public Inquiry [5] and an EIA process [15]. The disturbed area was relatively small as the nature of the ore-body allowed mining to be completed in one 143–day campaign in 1979. The ore was stockpiled whilst the mill was built. Milling continued until 1989 when the site was "mothballed" for 5 years whilst the mining company explored for new reserves. In 1994 the Supervising Authorities directed the mining company to rehabilitate the site, requiring that all site work should be completed by 31 December 1995. A full description of the remediation program has been given elsewhere [12, 15].

During the pre-mining negotiations with the Aboriginal traditional land owners it was agreed that the site was generally to be landscaped to match the original contours to the greatest extent practicable and revegetated to "blend in with the surrounding vegetation". Also, in accordance with the Environmental Requirements of the Commonwealth Government, all tailings were required to be returned to the mined-out pit. At Nabarlek, this was not a problem as the tailings had been placed in the pit as the stockpiled ore was milled [13].

Other criteria to be met for successful remediation were that the site should be safe to enable Traditional Owners to follow a traditional lifestyle without limitation on access. This would include hunting and food gathering across the site with occasional overnight camping. The issue of improving physical safety to meet the criteria was addressed by the dismantling, decontamination and removal of the mill and the associated infrastructure. All residual plant and machinery items that could not be sold or satisfactorily decontaminated were placed in the pit together with all other contaminated materials. Earthworks were completed in early December 1995, immediately before the anticipated onset of the wet season, thus allowing seeding to proceed at the optimum time. By mid-1996 there was an initial vegetation cover across the site. Since then tree growth has become uneven and introduced grass species are dominating some areas [12]. Enhanced planting of seedling trees raised from local provenance seed was sued to improve the situation and was looking successful but the whole region was severely affected by a cyclone in 2006 which has set back tree establishment and growth considerable. The enhanced planting programme has been re-instated and a new period of observation has begun.

Modern standards are exacting and the stakeholder community, including both regulators and landowners, is requiring that the satisfactory development of an "appropriate" climax vegetation association be adequately demonstrated before the mining company can be released from it's obligations for the site [12].

Ranger

Ranger is the only uranium mine currently operating in the Region. It is a conventional open cut operation with one active pit and one mined-out pit, which is the active tailings repository. Remediation planning at Ranger is seen by the stakeholders to be an example of best practice that stands as a benchmark for similar operations elsewhere in the region and the world. The five major elements of the program are:

- a clear understanding of the goal and objectives of remediation agreed by the stakeholders,
- stakeholder participation in the planning and updating processes,
- an approved plan for remediation that is revised annually,
- a process which ensures that the finance for remediation is completely secure, and
- implementation of progressive remediation wherever possible.

The remediation plan of the Ranger mine was set out initially in the EIS and was specifically written into the various agreements between the Traditional Owners, the Government and the mining company at the time development was approved. It was agreed that the final goal and objectives would be set down and agreed by the main stakeholders within a set period of time. This was finally achieved in 1990 [14] The goal is for the project area be rehabilitated to establish an environment which reflects that existing in the surrounding country and could permit the incorporation of the former site into the surrounding Kakadu National Park without detracting from the Park values or needing special management.

The mining company is required to revise the remediation plan annually for approval by the Supervising Authorities. The plan has to be sufficiently detailed for stakeholders to be confident that the goal and objectives would be met should the plan be implemented during its lifetime. The detail provided must be sufficient to enable a complete costing to be made. The mining company is then required to place a cash deposit in a remediation trust fund sufficient to pay for the approved plan. A complete blueprint for the total decommissioning of the site is currently being prepared by the company.

PHASE THREE OPERATIONS

Jabiluka

The Jabiluka project was the subject of a thorough EIA process and subsequent assessment by an independent scientific panel of the World Heritage Committee. After initial development of some underground works there was no agreement with the traditional owners for the full development to proceed at that time. The company agreed to backfill the workings, remediate the site and place it under long term care and maintenance. This work was completed in 2003. The mining company had previously provided a detailed remediation plan, which was assessed by stakeholders and approved by the Supervising Authorities in the same way as for the plan at Ranger. This approved plan was costed and the company had posted a guarantee for the entire remediation costs. This guarantee has been altered to take account of the changed situation at the site. Whenever the project moves into the next stage of development the plan will be updated as required. In the event that full development proceeds it is likely that the process of remediation bonding to be imposed will be similar to that employed at Ranger. Again a complete blueprint for decommissioning has yet to be prepared.

LONG TERM SURVEILLANCE AND MONITORING

A significant issue that remains unresolved is the stewardship or long term care of rehabilitated uranium mine sites [16]. There is a real concern that systems currently in place at present may rely on institutional controls too much in order to remain effective for the long term. Many members of the community consider that former uranium mine sites can never be regarded as completely safe, no matter how well controlled the remediation process has been.

Thus all remediation situations now require a plan for the site's long term stewardship. The major elements of stewardship are: appropriate monitoring and surveillance for as long as required (in perpetuity if necessary); provision of maintenance as required; ability to undertake further remedial actions if needed; and, communication and consultation with stakeholders. Few organizations other than central governments are likely to have the capability to provide adequate resources to manage the situation effectively and to the degree expected by the community.

Finally, the program of stewardship must include an element for consultation and information exchange with the stakeholders. Local communities must feel that they are being kept informed of the hazards and risks associated with a rehabilitated mine in their district and that they have real opportunities to contribute to decision making, especially in the stewardship period. The ultimate goal of stewardship must be to ensure that environmental protection is paramount and maintained at the required level.

CONCLUSIONS

Comparison of the remediation outcomes at Mary Kathleen and Nabarlek show how much standards have changed over time. A significant difference was that the Nabarlek EIS was drawn up after the Fox Report [5, 15]. Over the inquiry period (1975–77) it became apparent that society was no longer prepared to accept mining as a one-time user of land and former (legacy) sites would in future need to be returned to some form of alternative, and acceptable, land use. This would also be the case for all new developments. Furthermore, the Nabarlek plan was implemented long after it was drawn up and community expectations and technical standards had been raised considerably in the intervening years. The plan was continually updated in light of these developments [12]. However, the lack of objective standards has meant that agreement with stakeholders on the final completion of remediation has been difficult to achieve. The outcomes being planned for, and expected, at Ranger and Jabiluka represent a further shift and improvement in standards. Planning for these projects has benefited from the lessons learned elsewhere in the region.

The modern mining industry has developed a better understanding of the importance to consult frequently, extensively and effectively with stakeholders and systems are in place to ensure that funding for remediation is guaranteed. Remediation requirements and standards take account of community concerns and take account of concepts such as continuous improvement, sustainable development and inter- and intra-generational equity. Proponents who fail to consult with their stakeholders risk having their programs held up or even stopped in an atmosphere of conflict. As society has expressed its desire for ever better levels of environmental protection and remediation, so regulators have responded and the mining industry, in particular the northern Australian uranium mining industry, has acted to address those concerns and meet the new requirements through a process of continuous improvement.

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REGULATING URANIUM MINING REMEDIATION IN SAXONY/ GERMANY

S.Hurst[1], *F. Leder*[2]
[1]Saxon State Agency of Environment and Geology, Dresden, Germany
[2]Saxon State Ministry of Environment and Agriculture, Dresden, Germany

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Abstract

In 1990 in Saxony/Germany uranium mining remediation began. On the base of an eclectic legal background several licensing authorities had to find optimized procedures for a time saving but effective licensing process. Betimes it came to an agreement between the parties involved – operator and licensing authorities -, that early and comprehensive information as well as periodic meetings are an important base to meet the challenge. Further on the operators as well as the authorities informed the public about the planned measures as well as new developments. The operator mainly needs licenses from two authorities: the radiation protection authority and the mining authority. To make sure, that the decisions of both authorities are compatible continuous coordination is required. Finally all remediation planning is subject to long term sustainability.

BACKGROUND

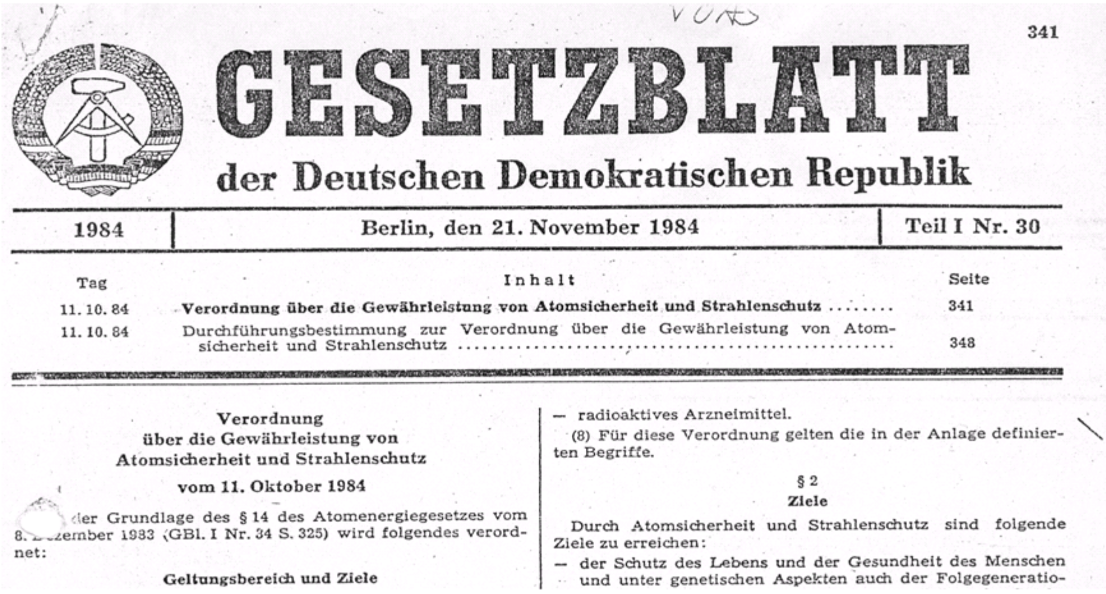
Until reunification the former GDR was number three of the top uranium producers in the world. Between 1945 and 1990 about 250.000 t of uranium ore were mined. In 1991 remediation started. Wismut GmbH, the former mining company (before: SDAG Wismut) was charged with the remediation of the tailings, waste rock and mining sites.

With the first remediation planning, intense communication between the main stakeholders in Saxony - the Saxon state, the communities and population living close to the sites, and the general public began.

The Federal Government, who is the owner of the Wismut sites, as well as the Saxon Government, have an interest in a speedy and efficient remediation that remains effective in the long term.

LEGAL BACKGROUND AND REMEDIATION GUIDELINES

In Germany the fundamental legal act for radiation protection is the Atomic Energy Act (Atomgesetz). The executive legislation for uranium mining remediation further on, is based on two radiation protection regulations. The 'Directive on the Assurance of Atomic Safety and Radiation Protection' (Verordnung über die Gewaehrleistung von Atomsicherheit und Strahlenschutz, VOAS) is a former GDR regulation that is still in force. Before reunification in Western Germany no specific regulation for uranium mining existed. In united Germany, remediation had to be initiated promptly, for which a legal basis was needed, so an agreement was reached to apply GDR-legislation. Additionally, in 2001 the Federal German regulation 'Directive on Radiation Protection' (Strahlenschutzverordnung, StrlSchV) was amended to cover radiation protection of the uranium mining remediation workers. For the public the dose limit of the VOAS (1 mSv/year) is still valid. Hence, all remediation measures aim for a long term limitation of the dose from former uranium mining and milling sites of 1 mSv/year — additional to the natural background.



VONS

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GESETZBLATT

der Deutschen Demokratischen Republik

1984	Berlin, den 21. November 1984	Teil I Nr. 30

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Verordnung
über die Gewährleistung von
Atomsicherheit und Strahlenschutz

vom 11. Oktober 1984

... der Grundlage des § 14 des Atomenergiegesetzes vom 8. ...zember 1983 (GBl. I Nr. 34 S. 325) wird folgendes verordnet:

Geltungsbereich und Ziele

— radioaktives Arzneimittel.

(8) Für diese Verordnung gelten die in der Anlage definierten Begriffe.

§ 2
Ziele

Durch Atomsicherheit und Strahlenschutz sind folgende Ziele zu erreichen:

— der Schutz des Lebens und der Gesundheit des Menschen und unter genetischen Aspekten auch der Folgegeneratio-

FIG. 1. Title page of the still valid GDR-Directive on the Assurance of Atomic Safety and Radiation Protection.

Regarding the remediation activities the following legal areas have to be considered:

— water protection issues are regulated by different European (e.g. European Water Framework Directive), federal (e.g. Water Balance Act/Wasserhaushaltsgesetz) and state law (e.g. Saxon Water Law);
— the legal basis for soil protection is the Federal Soil Protection law (Bundesbodenschutzgesetz);
— the Federal Mining Law (Bundesberggesetz) contents articles on the safety of mines, shafts etc.;
— federal and state laws on forestry are touched when e.g. trees had to be cut down; and
— federal and state laws on nature conservation are also sometimes touched (e.g. when biotopes worthy of protection exist on remediation sites).

REGULATORY PROCEDURES

As shown above, uranium mining remediation is touching several different legal areas. These areas are represented by different state authorities. Radiation protection in Saxony is under comes under the responsibility of the Saxon State Agency of Environment and Geology. Ground- and surface water as well as soil, forestry, nature conservation and mining issues are in the licensing responsibility of the Saxon Mining Agency. Although only two authorities are licensing uranium mining remediation, there are at least three more authorities (groundwater, surface water, soil) preparing scientific, technical and legal arguments for the licensing decision. This is important to make sure that all environmental issues are taken into consideration. On the other hand, the mining authority has the possibility to take its own decisions not only on the basis of the water and soil authorities, but also on the basis of (mining-) technical and economical feasibility. This complicated process is of fundamental importance for balanced decision making.

Further on the remediation (i.e. licensing and surveillance) of uranium mining sites requests the following circumstances be taken into account: (1) the existing radiological situation *(radon emanation, gamma dose rate, seepage water); (2) the existing contamination situation by other pollutants; (3) distances to population centers; (4) geotechnical stability; (5) the geochemical conditions (e.g. present and likely future development of water quality); and (6) the potential later use of the mine waste area or contaminated area.*

From these circumstances different regulatory responsibilities follow:

1. the existing radiological situation is needed by the radiation protection authority to evaluate the current and future exposure of the public;
2. distances to population centers, which are important for the calculation of radiological impacts on the public, are also of main interest for the radiation protection authority;
3. the existing contamination situation by other pollutants (e.g. heavy metals, organic pollutants) is an issue for water and soil protectio;
4. geotechnical stability is an issue for all environmental protection scopes;
5. geo(hydro-)chemical conditions have to be known by radiation, water and soil protection scopes; and
6. the potential later use is a fundamental aspect for the provision for future radiological and other exposure and in consequence for the planning of the remediation methods.

TABLE 1. LIST OF URANIUM MINING TAILINGS AND WASTE ROCK SITES IN SAXONY

Location	No. of objects	Area ha	Volume 106 m3	Tailings/waste rock
Aue	42 (Wismut GmbH)	345	47	waste rock
Königstein/ Gittersee	3 (Wismut GmbH)	38	5	waste rock
Helmsdorf	2 (Wismut GmbH)	218	50	tailings
Aue	1 (Wismut GmbH)	6.5	0.28	tailings
Old sites	ca. 3000 (diff.)			waste rock (total)
Old sites	ca. 300 (diff.)			waste rock (radiol. rel.)
Old sites	10 (diff.)			tailings

Uranium mining remediation in Saxony means the remediation of many different former mining sites (Table 1). Several hundreds of comparably simple licenses for routine work are needed on the one hand; on the other hand complex remediation plans for a huge tailings pond (Helmsdorf), several high-volume waste rock piles and additionally the flooding of four underground mines must be permitted.

COMMUNICATION PROCESSES BETWEEN REGULATOR, CONSULTANTS AND OPERATOR

Complex remediation problems need comparison of several alternative remediation methods, as a base for an ecological, radiological and economical optimization. In consequence continuous exchange between regulatory authorities, consultants and operator is inevitable.

For an effective licensing procedure communication between all parties and decision levels is needed. At the Saxon Radiation Protection Authority the following kinds of exchange were established:

- *Status meetings*: biennial meetings of superiors from operator and superiors and persons in charge for the sites from the rad. prot. authority; exchange on the general state of all relevant decision processes of all relevant applications; information on planed new applications; general (not detailed) discussion of different views and conceptions of remediation methods; protocol on agreement.
- *Application kick-off*: when a new application for a complex remediation project is filed the persons in charge of the operator present it to the persons in charge of the licensing authority; in most cases consultants of both parties are present; a first detailed discussion clears the general position of the authority; the operators are charged with the first adjustments and additions; protocol on agreement.
- *Project meetings*: frequency as necessary; detailed discussion of scientifical, technical and/or advisory questions regarding applications or licenses; between persons in charge of both parties and consultants: protocol on agreement.
- *Mail and phone*: frequency as necessary; short questions for smaller problems, were no protocol is needed.
- *Scientific workshops*: authority or operator invites (international) experts to give presentations on special scientific questions regarding uranium mining remediation; panel discussions; proceedings.

In some cases also project meetings and other communication between different authorities have to take place to clear and harmonize positions before the authorities meet the operator.

Subjects of discussion and workshops are e.g.:

- radiological measurements and situation of a site,
- ecological situation (other contaminants than radioactive),
- monitoring of subjects (frequency, sites etc.),
- geo(hydro) chemical modeling of subjects (thermodynamic data base),
- geotechnical remediation methods,
- cost reduced methods like ecological engineering (may be more effective than expensive solutions),
- data management and exchange,
- long term regulations and responsibilities.

Benefits

Elementarily the exchange supports the following aspects:

- trust in the competence of the concerned parties;
- weighed out and adjusted solutions;
- scientific and state of the art solutions;
- cost saving remediation;
- long term safe remediated sites.

COMMUNICATION WITH OTHER STAKEHOLDERS AND INFORMATION OF THE PUBLIC

Especially in the beginning of the planning and remediation activities in the early 1990s, several local non governmental organizations (NGOs) as well as representatives of local communities were questioning the fate of "their" sites. At some sites NGOs and communities even organized their own workshops and invited representatives of operators and authorities to present their solutions for the remediation.

The press as another stakeholder was reporting about these activities and, after publishing the first reports about some sites as "Death-Valleys" this unsettled the population and the operator at first, to deal regularly with the subject in a balanced way.

In response to first press releases, the operator fortunately started a policy of transparency straight away.

Also the regulator handles information very openly. However, after the application for license has formally reached the licensing authorities, no information is passed on to third parties reagarding the state of the process until the subject is licensed. When it is licensed, third parties can go to court to oppose it if they are concerned by the decision. To make sure that concerned persons or communities' interests are taken into consideration, the operator or the authority informs them before the remediation planning starts. Discussions with communities take place regarding the future use of the sites, for instance if another use such as forestry is allowed by the law. When for example a golf course, riding/parking areas or model plain airports are planned (as was the case in one community) the cover of the waste rocks must be developed in a different way than for forestry use.

The regulators mainly inform the public by their websites. Due to the Act of Free Information the authorities in Germany have to disclose all data to the public. On the websites everybody can find the names and e-mail addresses of the responsible officers and is thus able to get all information needed.

Benefits

- trust in the competence of the operators and the regulators
- time and money saved
- communities know about problems and thus are able to plan according to them.

SCIENTIFIC EXCHANGE

From the beginning of the early 1990s up to present day, scientific exchange is one of the most important bases for decision making in uranium mining remediation. The Saxon State Ministry of environment and agriculture initialized in the early 1990s a scientific congress that since 1995 has organized and performed biennial or triennial by the Technical University of Freiberg/Saxony (Uranium Mining and Hydrogeology). All presentations are published as proceedings by SpringerMedia [1].

As mentioned above, workshops on specific scientific questions (radiological, geo(hydro)chemical, geotechnical etc.) are part of the decision making. In some cases only a dozen persons took part, in some cases up to 120 persons were in invited and took part.

In 1993 two federal ministries (Environment and Economy) initiated an international exchange of experts in uranium mining remediation (now UMREG). This exchange, which took place for several days in the beginning and was combined with field trips, helps to get an overview over international experience and methods already put into practice.

Additionally, a guideline on uranium mining remediation was published by the Saxon Ministry of Environment in 1997. It gives information on the legal background, the procedere for remediation and long term issues. Furthermore, it has comprehensive appendices on international legislation, radiological and health aspects, data sources, radiological assessment, water path issues, soil and plant path issues, geotechnical questions, remediation methods, use of remediated sites, long term monitoring and it gives addresses of authorities and institutions. It is also published in the internet.

Benefits

- sharing experience saves expenditures.
- new developments are encouraged.
- exchange gives confidence in a safe appliance of new developments.

DOSE LIMITS AND MAXIMUM CONCENTRATION LIMITS

One of the first questions is that for the radiological and ecological goal of the planned remediation [2]. International dose limits and maximum concentration limits show a limited spectrum of values for radionuclides e.g. in water.

§7 of the German Drinking Water Regulation of May, 21. 2001 says that "…in water for human consumption indicator parameters of the standards in attachment 3 have to be followed". Attachment 3, number 20 says, that a total individual dose of 0.1 mSv/a is allowed. This regulation includes all radionuclides except of H-3, K-40, RN and RN daughters. With this paragraph a corresponding regulation of the European Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption came into force for Germany [3].

The radiation protection regulation of 20 July 2001 gives Standards for the ingestion of radionuclides with drinking water. Looking at the standards for infants from 0 to 1 year age one can calculate concentrations for different natural uranium isotopes from 1.59 to 1.73 Bq/L (128 to 130µg/l)

In all these Regulations uranium is only considered as a radionuclide, not as a heavy metal. Uranium as a heavy metal causes kidney diseases and is, if ingested, much more toxic than as a radionuclide [4]. The world Health Organization (WHO) has established a tolerable daily intake (TDI) for uranium of 0.6 µg/kg body weight and day. This is based on adverse affects observed by Gilman et al. [5]. The WHO provisional guideline for drinking water quality recommends 15µg/l uranium per liter as a standard.

On the base of theses studies Germany decided in 2006 to recommend 10µg/L as MCL for drinking water.

International standards are also taking the chemical toxicity of uranium into consideration, e.g.:

- Health Canada: 20 µg/L.
- US EPA (drinking water): 30 µg/L
- US EPA (remediation goal): 2.22 µg/L
- US NRC: 14.8 g U/year (oral ingestion)
- Australia (drinking water): 20 µg/L.

MONITORING, MAINTENANCE AND LONG-TERM RESPONSIBILITY

Monitoring subjects are water (seepage, flooding, ground, surface), air (radon), covers (damages, slides, erosion). Subjects and frequency of monitoring are part of the licenses. Monitoring scale will be reduced stepwise with time.

In Germany the operators, respectively owners, and the authorities (radiation protection and mining) are responsible for monitoring during and after remediation.
The long term maintenance of the remediated sites comprehends the following activities:

- taking care for stability of remediation measures (mending defects of covers, watching growth (quality) of plants, etc.
- planning new measures if remediation methods turn out to be ineffective.

If the remediated sites are used by a new owner (e.g. Golfpark Schlema), the responsibilities still remain with the former operator.

Radiological long term goal of the remediation effect for the public is max. 1mSv/a and 50mSv/lifetime (VOAS). Remediation measures are claimed to remain stable for 200 to 1,000 years. All licenses include long term monitoring and maintenance conditions and the monitoring and maintenance program for waste rock piles and tailings ponds is covering at least 15 years. The steps in the development of the process from remediation to stewardship are shown in Figure 2.

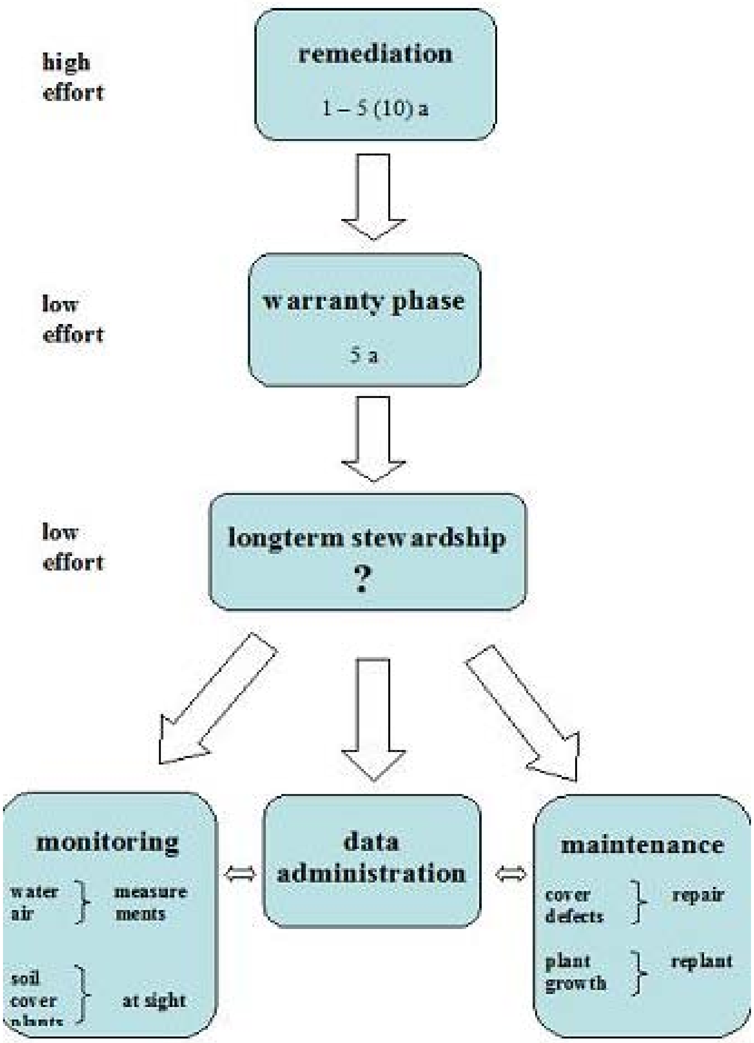

FIG.2. shows the three steps after mining to long term stewardship.

To keep information about the remediation records for different monitoring issues have to be stored in different ways.

Documents may be stored as papers, digital files or data bank updates and maintained in paper archives or data bank systems. In Saxony the data bank KANARAS (catasternfor natural radioactivity in Saxony) is consisting of:

- Wismut data bank (Wismut sites);
- A.LAS.KA (radiological data of old sites, federal prod.);
- FbU (radiological and geographical data of old sites);
- DURAS (radiological analyses of saxon state lab).

The paper documents will be kept in the state archive (at least for 25 years).

Costs for long term activities of sites owned by the federal government are paid by the federal state. The idea to give monitoring and maintenance money to Saxony or to a monitoring and maintenance company is not into practice yet.

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THE NAVAJO NATION'S MINE LAND RECLAMATION AND URANIUM MILL TAILINGS REMEDIAL ACTION PROGRAMS

M.Roanhorse
Division of Natural Resources, Navajo AML/UMTRA Department, Window Rock, AZ, USA

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Abstract

The paper provides a brief overview of the activities of the Navajo nation's work in remediating former uranium mining and processing sites on their lands.

INTRODUCTION

The Navajo Abandoned Mine Lands Reclamation (Navajo AML) and Navajo Uranium Mill Tailings Remedial Action (Navajo UMTRA) manage the environmental programs pursuant to the federal and Navajo Nation Laws. The Navajo AML has the authority and responsibility to provide and conduct reclamation of abandoned coal and non coal mines (uranium, copper, and sand/gravel) within the jurisdiction of the Navajo Nation pursuant to the Public Law 95–87, Surface Mining Control and Reclamation Act of 1977 (SMCRA), as amended, and the Navajo Reclamation Code/Plan.

The Navajo land is located within the exterior boundaries of the States of Arizona, New Mexico and Utah. It is located on approximately 25 000 square miles, equal to 62 750 square kilometres. 62 750 million acres are equal to 6 480 000 hectares. Nearly 1300 abandoned mine sites have been identified and most sites about 90% have been completed. Mine features include open pits, rimstrips, vertical and incline shafts, open portals, associated radioactive mine waste and structures.

AML MINE WASTE RECLAMATION

In general, earthwork requirements are excavation, loading, hauling, backfilling, grading and compaction of radioactive mine waste. Mine waste piles are used as backfills inside mine openings, against highwalls, and/or contoured in designed burial areas and make sure the waste is free from combustible materials such as wood products, trash, and vegetation. Certain radioactive mine waste piles are buried in place by reducing the side slopes, grading/contouring and covering with clean material, see below of the soil classification of mine waste materials:

- **Class A:** Mine waste piles, overburden, subsoil, topsoil or other suitable material with Ra–226 concentration equal to or less than the average Ra–226 concentration of the background area in the vicinity of the project as computed from ground and/or contact radiological measurements. The material is free of solid waste, hazardous waste, toxic waste, vegetation and combustible materials.
- **Class B:** Materials similar to Class A but materials with the Ra–226 concentration above that of the background but not exceeding 25 pCi/g.
- **Class C:** All other mine waste piles, overburden, protore or subsoil material whose Ra–226 concentration exceeds 25 pCi/g.

Typical excavation and backfilling sequence are as follows:

- Class A and/or Class B material are excavated out from the designated waste piles, hauled to the designated Class C mine waste burial areas and placed as the bottom layer as a buffer zone. The thickness of the layer is usually three (3) feet depending on the availability of the material.
- Class C material is excavated out from the waste piles and placed over the buffer zone or as the bottom layer, in case buffer zone was not place due to shortage of Class A/B type of materials.
- Class B material, if available, is excavated out from the waste piles and placed in the openpit(s) on the top of the Class C materials.
- The final layer of minimum 1 1/2 feet thick Class A materials from the waste piles, overburden pile and/or other designated borrow source is placed over the Class C materials to construct the final cover of the reclaimed area.

Earthwork is in a fashion that eliminates or minimizes erosion. The reclaimed areas must meet the Navajo AML's in-house cleanup guidelines. Water is required during backfilling for dust control and to achieve the required compaction. Consultation is essential with respective agencies such as Army Corp of Engineers and US Environmental Protection Agency (EPA) to discuss the Navajo AML environmental problems that cannot be reclaimed pursuant to the goals of SMCRA. A monitoring program for the reclaimed AML sites has been implemented for the maintenance work if necessary.

NAVAJO UMTRA

The U.S. Department of Energy (DOE) in close coordination with the Navajo UMTRA and Nuclear Regulatory Commission (NRC) is responsible for remedial action of four (4) Navajo UMTRA Sites. These sites are located in Tuba City, Arizona; Mexican Hat, Utah, Monument Valley, Arizona; and Shiprock, New Mexico. First phase consisted of surface remedial action at the UMTRA sites which begun in October 1984 and completed in February 1995. All surface contaminated materials and associated debris were placed and stabilized in disposal cells pursuant to U.S. EPA standards in 40 CFR Part 192.

Long Term Surveillance Plan was developed by DOE to ensure annual inspections are performed. Corrective actions are taken on extreme natural events, vandalism, or other events that may threaten the stability of the disposal cell. So far, no major problems have been noted.

The second phase of remedial action is the ground water cleanup pursuant to Federal and Navajo Nation regulations. All sites are proposed for active ground water remediation except for Mexican Hat UMTRA site which is proposed for no remediation. For example, DOE's remedial action plans for Tuba City UMTRA site include the following:

- Extraction wells are used for pumping out contaminated ground water at a rate of 100 gallons per minute for treatment;
- The extracted ground water is treated with an ion-exchanged and a distillation process to remove most contaminants;
- Ground water that has been treated is returned to the aquifer through injection wells and an infiltration trench;
- The contaminants (brine) are pumped to an evaporation pond. Eventually, the brine will be taken off site for disposal. About 90% of the extracted, treated water is preserved.

The approach for Shiprock UMTRA site is extraction of contaminated ground water from the aquifers and placed into an evaporation pond; no treatment system was setup. Navajo UMTRA assists DOE with monitoring of ground water remediation in Tuba City and Shiprock. DOE has implemented phytoremediation pilot study at the Monument Valley UMTRA site. If the pilot study shows that this cleanup method works for Monument Valley site, it will be considered it for the long term ground water cleanup efforts. DOE abides by all federal and Navajo Nation cleanup standards. Ground water cleanup has been complex and challenging work for DOE and has been a learning process for the Navajo UMTRA.

Navajo UMTRA will continue to assist DOE with ground water remediation activities and long term surveillance and monitoring program.

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