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Uranium Production Cycle Selected Papers 2012–2015

Proceedings of a Series of Technical Meetings

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International Atomic Energy Agency

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PROCEEDINGS OF A SERIES OF TECHNICAL MEETINGS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2019

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Printed by the IAEA in Austria
June 2019

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Uranium production cycle selected papers 2012–2015 / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2019. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1873 | Includes bibliographical references.
Identifiers: IAEAL 19-01241 | ISBN 978–92–0–103019–1 (paperback : alk. paper)
Subjects: LCSH: Uranium cycle (Biogeochemistry). | Uranium industry. | Uranium mines and mining.

FOREWORD

Since 2009, the expected growth of nuclear power worldwide has led to an ongoing increase in uranium demand. Notwithstanding significant price fluctuations, uranium production has increased over the past several years, and many new projects are now under consideration. Negative legacies of past uranium mining activities have the potential to impact current and proposed uranium mining projects, in particular their ‘social licence’. Much work has been done to remediate those negative effects in many mining districts, although much remains to be done. Moreover, some currently operating mines are nearing the end of their active lives and will move into rehabilitation in the next few years with a need to avoid new legacy issues.

The IAEA undertakes numerous activities to support its Member States throughout the life cycle of uranium production and in the remediation of legacy sites. In the 1990s, the IAEA began working with the Uranium Mining and Remediation Exchange Group (UMREG), an informal international assemblage of uranium mining professionals that brings together practitioners from all sides of the uranium mining industry to discuss ideas and exchange experiences related to remediation and legacy site management, and operational mining projects. In 2011, the IAEA published a volume of collected papers entitled UMREG Uranium Mining and Remediation Exchange Group: Selected Papers 1995–2007.

In 2012, the IAEA began a further series of nine Technical Meetings on the theme of good practice in the uranium production cycle, including an UMREG meeting hosted by the IAEA at its Headquarters in Vienna. The committee advising the IAEA for these Technical Meetings urged publication of a second volume of collected UMREG papers, and so the proceedings of the UMREG meeting were expanded to include selected papers from other Technical Meetings within the series. The present publication is intended to be a record of the work done in many Member States and presented at UMREG and other relevant Technical Meetings over the period 2012–2015. It includes all of the papers received, in the order in which the original presentation was made. For the majority of the papers, the work has been updated since the original presentation, and the title and authorship may vary slightly to reflect this.

The IAEA officers responsible for this publication were P. Woods and M. Fairclough of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

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SUMMARY

This collection of papers has the common theme of good practices in the uranium production cycle. They were presented at several IAEA technical meetings (and in one case, a consultancy meeting) over four years. The collection provides a valuable opportunity to record and disseminate information presented at meetings for which insufficient manuscripts are available to justify stand-alone proceedings. As such, an outline of the meeting at which the paper was first presented will be provided, followed by a summary of the paper or papers based on talks given at that meeting. For some of the meetings, the unedited and unreviewed presentations themselves are available from the IAEA web site. Papers presented here may vary slightly in title and wording compared to the corresponding presentation, due to the review and editing process. In the majority of cases the information in the papers has been updated compared to the original presentation, which has also led to some changes of authorship and title.

TECHNICAL MEETING ON THE ORIGIN OF SANDSTONE URANIUM DEPOSITS: A GLOBAL PERSPECTIVE, VIENNA, AUSTRIA, 29 MAY–1 JUNE 2012

The purpose of this technical meeting was to provide a forum for experts from Member States to discuss recent advances in understanding the origin of sandstone uranium deposits and using this insight in exploration programmes for identifying new resources. Recent case histories and geological/exploration studies of sandstone uranium deposits were discussed.

The following specific topics had been identified as being of particular interest, and were to be considered in the papers to be presented:

- Geological setting and controls of sandstone uranium deposits;
- Origin of sandstone uranium deposits;
- Mineralization styles of sandstone uranium deposits;
- Recognition criteria for sandstone uranium deposits;
- Geochemical and geophysical exploration for sandstone uranium deposits;
- Exploration and production case histories of sandstone uranium deposits;
- Socioeconomic and environmental issues in production from sandstone uranium deposits.

The meeting was chaired by M. Cuney (France). The IAEA officer responsible was H. Tulsidas. Forty-five talks were listed in the agenda of the meeting. The following summarizes the paper included here.

Geology of the Kayelekera uranium deposit, Malawi

A. Wilde (Australia) presented on the geology of the Kayelekera uranium deposit, Malawi. Kayelekera is a tabular sandstone-hosted deposit hosted by Permian carbonaceous and pyritic arkoses of the Karoo rift–fill sequence. With an average mined grade in excess of 800 ppm U_3O_8 (~680 ppm U) the deposit is higher in grade than most comparable deposits in the East African Karoo basins. The age of primary mineralization remains poorly constrained, but the deposit could be a product of Permian rifting. An important feature of the mineralization and which has contributed in no small part to the higher grades is overprinting by secondary processes which the authors infer are related to movement on NW–SE–trending Tertiary normal faults. This overprinting occurred after the arkoses had been rendered impermeable by clay cementation. Kayelekera was the first, and to date only, uranium mine to open in Malawi, with commercial production declared as of 1 July 2010.

URANIUM MINING REMEDIATION EXCHANGE GROUP 2012 (HELD AS A JOINT SESSION WITHIN ENVIRONET ANNUAL FORUM 2012) VIENNA, AUSTRIA, 7–8 NOVEMBER 2012

The IAEA's ENVIRONET initiative [1] holds annual forums. The purpose of ENVIRONET is to[1]:

- Coordinate support to organizations or Member States by making available the relevant skills, knowledge, managerial approaches and expertise, related to environmental management and remediation;
- Offer a broad and diversified range of training and demonstration activities with a regional or thematic focus providing hands-on, user-oriented experience and disseminating proven technologies;
- Facilitate sharing and exchanging knowledge and experience among organizations with advanced environmental management and remediation programmes;
- Collect and share the good remediation practices by identifying and treating improper past operations, thus assuring the longer-term knowledge;
- Provide a forum in which experts' advice and technical guidance may be provided.

During the 2012 ENVIRONET forum, one and a half days were allocated to the Uranium Mining Remediation Exchange Group[2]. Twenty-one talks were presented on the general theme Creating Conditions Conducive to Remediation of Uranium Production Legacy Sites and Safeguarding an Economically and Environmentally Balanced Uranium Production Cycle. Three resulting papers were prepared and included in this report. The IAEA officer responsible was H. Monken–Fernandes.

Best practice in environmental management of uranium mining — IAEA recommendations

P. Woods of the IAEA spoke on the IAEA's recommendations for best practice in environmental management of uranium mining, expanding on a 2011 Nuclear Energy Series Technical Report [2]. The IAEA has supported good practice in the mining and extraction of uranium and thorium worldwide over the last several decades and will continue to do so. Further to its well-known safety standards for radiation protection, regarding the uranium production cycle it has produced guidance and acts as a gatherer and provider of information on technological, environmental, regulatory and geological aspects. The theme is addressed by many IAEA activities spread across its different departments, including through a number of Technical Cooperation projects throughout the world. The basic guiding principles are based on those of Sustainable Development, the ALARA (as low as reasonably achievable) Principle and the Precautionary Principle.

The application of best practice principles for a project begins at the conceptual phase and continues through all of the stages of the project, from exploration and conceptual design, through construction, operation, to closure and post-closure stewardship. The IAEA's

[1] See also http://www.iaea.org/OurWork/ST/NE/NEFW/WTS-Networks/ENVIRONET/overview.html

[2] Since renamed Uranium Mining and Remediation Exchange Group, with a broader approach to include current and planned uranium mine sites.

recommendations are generally consistent with those produced by other international bodies and have parallels in recent specific guidelines produced in some of its Member States.

Remediation of uranium mining and milling legacies at the Mailuu Suu site (Kyrgyzstan) — achievements and lessons learned during implementation of the 'disaster and hazard mitigation project' 2005–2012

This topic was addressed by C. Kunze (United Kingdom) on behalf of a team. He described remediation measures at the former mining and processing site of Mailuu Suu (Kyrgyzstan) under the Disaster Hazard Management Project of the World Bank as the first large scale works that have successfully been implemented at Central Asian uranium legacy sites. The approach to justification and optimization of the environmental remediation strategy at the Mailuu Suu was outlined, including financial and timing constraints, the various remedial measures that have been implemented to date, and lessons learned that may inform the way forward at this and other legacy sites in Central Asia. An overview of temporary and sustainable remediation works was given. The key role of stakeholder involvement, trust building and communication at all stages of the conceptual preparation, planning and implementation of the remediation measures was emphasized. The paper also suggested useful lessons that were learned in relation to temporary stabilization works that could not be followed up at the time with more sustainable measures due to administrative and financial constraints.

Uranium mill tailings affecting water resources in Mailuu Suu Valley, Kyrgyzstan

In a companion talk F. Wagner (Germany) gave a further perspective on an important aspect of the work in Kyrgyzstan, the effect of uranium mill tailings on water resources. These potential effects are a driving force for some of the remedial works being undertaken and planned in this former uranium mining and milling area. On behalf of a team he described a monitoring and investigation programme started in 2006 to examine the issue and understand uranium mobilization and transport paths. The status of local water resources and recommendations for remediation measures were presented to the local authorities and citizens.

TECHNICAL MEETING ON OPTIMIZATION OF IN SITU LEACHING (ISL) URANIUM MINING TECHNOLOGY, VIENNA, AUSTRIA, 15–18 APRIL 2013

This meeting provided a forum for experts from Member States to present, discuss and disseminate practical know-how and innovative knowledge related to the ISL technique for uranium mining, with an emphasis on advances in the design and operations of uranium mine and ISL plants, including improvements based on mining experience and other innovations. Eighteen contributions covered recent advances in ISL uranium mining projects, from exploration to mining and remediation stages, and some broader topics. Most Member States involved in ISL uranium mining were present, with others considering possible ISL mining in the future. The IAEA officer responsible was P. Woods. Two manuscripts based on presentations at this meeting are included in this report.

Extraction of uranium from monazite sand in Thailand

U. Injarean (Thailand) presented on a topic within the broader topic of uranium supply, discussing the progress made in Thailand with the technology of extracting uranium from monazite sand, extracted as a by–product of tin mining in the region. Monazite is better known as a source of Rare Earth Elements and Thorium, but the Thai work has demonstrated that uranium can also be recovered as part of processing for these products. The original concentrations of thorium and uranium in the monazite were 5–10% and 0.3–0.8% respectively. Uranium and thorium were recovered as a mixed hydroxide using an alkali process, and the uranium separated by solvent extraction using 5% tributyl phosphate in kerosene. Further purification was required to obtain a high purity uranium product.

Reactive transport simulation of uranium ISL at the block scale: a tool for testing designs and operation scenarios

Advances in the modelling of the extraction of uranium during leaching in the field were described by O. Regnault of France. A 3–D reactive transport modelling approach has been developed dedicated to simulate acid ISL production of uranium. The model relies on an appropriate description of uranium bearing aquifer via a 3–D geological model, based on geostatistical simulation of uranium grade and hydrodynamic parameters. Also, a correct assessment of the chemical reactions at stake is necessary. The ISL operations are then simulated using the versatile reactive transport code HYTEC. Among other simulation results available, the evolution of the uranium concentration at production wells can be predicted. This model was then applied to a field mining example at the KATCO mine in Kazakhstan and found to reproduce the behaviour in terms of uranium recovery and acid consumption. The verified model can then be used to compare production scenarios for the optimization of production.

TECHNICAL MEETING OF THE URANIUM MINING AND REMEDIATION EXCHANGE GROUP (UMREG–2013), DOLNI ROZINKA, CZECH REPUBLIC, 26–30 AUGUST 2013

General

This technical meeting allowed experts from Member States to present, discuss and disseminate practical know-how and innovative knowledge related to the environmental aspects of uranium mining and remediation projects. It provided a networking forum and opportunity for the transfer of knowledge and experience from the senior members of the industry to the newly developing producers and their staff responsible for the development of uranium resources, thus helping them to include postmining and processing issues at the stages of resources development and production, and contributing to the successful progressive rehabilitation and closures of the uranium production cycle.

The IAEA officer responsible was P. Woods. Five manuscripts based on presentations at this meeting are included in this report.

History of the Uranium Mining and Remediation Exchange Group (UMREG)

A history of the Uranium Mining and Remediation Exchange Group (UMREG) is provided in the paper by P. Waggitt (Australia), a member of the group organizing meetings prior to 2012. UMREG was founded in 1993 from a series of meeting between experts from Governments of the USA and Germany who shared a common challenge in having to deal with the remediation of uranium production facilities that were, in part, a legacy of the Cold War era. In time the meetings became more international, including some of the Central Asian countries where uranium processing had been abandoned after 1989 at the time of the dissolution of the Soviet Union. UMREG had no permanent source of funds and the meetings were often held as adjuncts to other technical meetings and conferences. The association between UMREG and the International Atomic Energy Agency (IAEA) has been a long one and has resulted in two important outcomes: the production of a monograph of selected UMREG papers, published in 2011[3]; and the incorporation of UMREG into the programme of the IAEA's uranium production cycle activities. Independently, a not-for-profit society known as UMREG Incorporated[3] was established in 2014, and has supported the IAEA UMREG programme as well as organizing activities of its own. These history and plans are set out in the paper.

Uranium mining regulation and legacy site remediation funding in Australia's Northern Territory

P. Waggitt (Australia) described regulation and legacy site remediation funding of uranium mining in the Northern Territory of Australia. The complex regulatory system is controlled primarily under the Northern Territory *Mining Management Act*, but with a number of additional processes and procedures involving the major stakeholders in a consultative manner, some of which are site specific. The process has developed over many years to the present state where it may be considered a mature and efficient system. Regulatory oversight at the one currently-active uranium mine and mill in the Northern Territory, the Ranger mine, was described. There have been a number of historic operations of various sizes; of these Nabarlek, Rum Jungle and the South Alligator Valley mining field were briefly described, as were plans for the yet undeveloped Jabiluka and Koongarra projects.

The paper goes on to describe the Northern Territory Government's approach to fund a legacy mines unit and the proposed programme of works for that unit, including work in relation to former uranium mine sites.

An overview of in situ leach uranium mining and associated remediation issues

The IAEA has prepared an overview report to show how in situ leach (ISL) experience around the world can be used to direct the development of technical activities, taking into account environmental considerations and an emphasis on the economics of the process, including responsible mine closure [4, 5]. With this report Member States and interested parties have more information to design and efficiently and safely regulate current and future projects, with a view to maximize economic performance and minimize negative environmental impact. P. Woods (IAEA) presented highlights of the report's findings with a summary of the IAEA's involvement in ISL over recent decades and some discussion on ISL remediation issues.

Remediation of former uranium in situ leaching area at Straz Pod Ralskem–Hamr Na Jezere, Czech Republic

M. Kroupa (Czech Republic) gave an overview of uranium remediation of former ISL uranium mines in northern Bohemia. After decades of mining, the Czech government decided to liquidate the ISL uranium mine at Straz Pod Ralskem–Hamr Na Jezere, and started remediation in 1996. The extensive remediation works were described, with an emphasis on the preparation of remediation targets and changes and improvements in recent years. The remediation action consists of: pumping of residual solution to the surface, separating uranium from the solution and reprocessing contaminants into commercially usable or ecologically storable products. It is projected that the site remediation targets should be met by the remediation project in 2037.

Status of the Moab UMTRA Project long term remedial action

The paper by D. Metzler (USA) describes progress at the Moab Uranium Mill Tailings Remedial Action (UMTRA) Project in south–eastern Utah. Systems were designed and

[3] http://umreg.net/

constructed in 2008 and 2009 for moving the 14 Mt of uranium mill tailings away from the Colorado River and permanently storing them in a disposal cell being constructed 48 km north near Crescent Junction, Utah. From design and infrastructure construction through the operational phase of the project, the highest priority has continued to be placed on workplace safety. Current and anticipated project funding supports the moving of 540 000 to 590 000 tonnes each fiscal year. Based on the approved lifecycle estimate, at the time of presentation the project was ahead of schedule and trending below the originally estimated cost for completion.

TECHNICAL MEETING ON URANIUM PRODUCTION CYCLE PRE-FEASIBILITY AND FEASIBILITY ASSESSMENT, VIENNA, AUSTRIA, 7–10 OCTOBER 2013

The purpose of this meeting was to provide a forum for experts from Member States to present, discuss and disseminate practical know-how and experience related to conceptual, pre-feasibility and feasibility studies and assessments for uranium mining.

The presentations and discussions at the meeting:

- Gave examples of information and activities to be done concurrently with mid to late stage exploration that can save time, money and effort with conceptual, pre-feasibility and feasibility studies;
- Provided information on knowledge, process characterization concepts, technologies, metallurgical testing and process flowsheet development that go into staged conceptual, pre-feasibility and feasibility studies and assessments;
- Considered technological, economic, social, regulatory and environmental aspects of the development and assessment of uranium mining projects from early assessment towards development;
- Integrated geological exploration, resource estimation and definition into the various study stages;
- Integrated environmental and social licensing issues into the various study stages;
- Gave example studies of uranium deposits at different stages of conceptual, pre-feasibility and feasibility studies, including projects that went on to production, are continuing to be developed, or have been assessed and shelved;
- Showed how the principles of conceptual, pre-feasibility and feasibility assessment should also be applied to closure planning for emerging projects, active mine sites and legacy site remediation.

The IAEA officer responsible was P. Woods. Two manuscripts based on presentations at this meeting are included in this report.

The role of mineralogy in process engineering

G. Dunn (Australia) gave a paper describing the role of mineralogy in process engineering as related to the milling of uranium ore. There are many different types of uranium minerals and their processing routes are often dictated by the types of uranium and gangue minerals in the ore. Mineralogy provides the insights into chemical as well as physical requirements to process the ore, and enables the degree of liberation and the grain size of the uranium and the gangue minerals to be determined. These in turn provide insight into the comminution circuit required to present the liberated ore to the leach. Mineralogy is an essential input into the mass balance design basis. The paper examines the role of mineralogy in process engineering in general and demonstrates its application through a detailed case study of a project with a uranium ore grade of 400 ppm U.

Role of test work in process engineering of uranium circuits

In a companion paper G. Dunn examined the different options in flowsheet selection and the role of test work in process engineering of uranium circuits. Uranium is found in a variety of minerals with ores over a very large range of concentrations, from >10% U for some Canadian projects to <0.1% U in some other locations. After general considerations, Case Study One in the southern hemisphere was presented, and test work for leaching, solid-liquid separation, uranium recovery and product precipitation was described. For Case Study Two work done for the ore preparation unit operation was described.

TECHNICAL MEETING OF THE URANIUM MINING AND REMEDIATION EXCHANGE GROUP (UMREG), FREIBERG, GERMANY, 23–24 SEPTEMBER 2014

The 2014 Technical Meeting of the Uranium Mining and Remediation Exchange Group (UMREG) was on the margins of the Seventh International Conference on Uranium Mining and Hydrogeology hosted by the Freiberg University of Mining and Technology in Germany. The meeting brought together practitioners, technologists, environmental workers, miners, operators, researchers and regulators to exchange information and discuss approaches to current technological, social and environmental issues related to uranium mining and remediation activities in all phases of the uranium production cycle. The IAEA officer responsible was P. Woods. One manuscript based on presentations at this meeting is included in this report.

Applying the Safety Conscious Work Environment at U.S. Department of Energy radioactive waste cleanup sites

Further to the technical paper on the Moab UMTRA Project long term remedial action presented at the 2013 Technical Meeting of the UMREG and also included in this report, D. Metzler (USA) emphasized the importance of safety in a uranium legacy site remediation project. At such sites the U.S. Department of Energy's (DOE's) ultimate safety objective is to have zero accidents, work-related injuries and illnesses, regulatory violations and reportable environmental releases. The concept of a 'Safety Conscious Work Environment' (SCWE) is applied. The paper describes the commitment to safety and health that underlies the approach of the DOE, and describes SCWE as a journey. After describing the general principles, a case history of the Moab Project was presented, where the SCWE approach was introduced in 2013. For SCWE to take hold and work in a sustained manner, there is a dependence on employees believing that the organization supports continuous improvement and effective resolution of problems, while encouraging the sharing and utilization of operational experiences. Recently, an outside audit team assessed the Moab Project and concluded that the project had a healthy, functioning SCWE. The ongoing challenge is to sustain this progress.

THIRD CONSULTANCY MEETING FOR THE PREPARATION OF AN IAEA PUBLICATION ON THE MAJOR ENVIRONMENTAL CONSIDERATIONS ASSOCIATED WITH URANIUM MINING AND MILLING, VIENNA, 23–27 MARCH 2015

This meeting was held in preparation for an IAEA publication on the major potential environmental issues that may occur as a result of activities during the pre-production, production and post-production phases (but not remediation per se) of uranium mining and milling. As part of the preparation, presentations on two topics were given. The IAEA officer responsible was M. Phaneuf. One manuscript based on a presentation at this meeting is included in this report.

An overview of uranium milling processes, associated wastes and atmospheric releases

A. Sam of the IAEA Monaco Laboratory presented an overview of conventional uranium milling processes, extraction of uranium as a by-product from non-conventional resources, wastes generated from milling operations and airborne radioactive and chemical effluents. This was within a wider scope of a high-level document that primarily intended to provide non-exhaustive technical information. After describing the milling processes important aspects of the associated wastes and atmospheric releases from uranium milling are discussed.

TECHNICAL MEETING OF THE URANIUM MINING AND REMEDIATION EXCHANGE GROUP, BAD SCHLEMA, GERMANY, 31 AUGUST–1 SEPTEMBER 2015

This third IAEA Technical Meeting (TM) of the Uranium Mining and Remediation Exchange Group (UMREG) was held on the margins of the WISSYM 2015 International Mining Conference organized by Wismut GmbH [6]. WISSYM 2015 was itself an official cooperation meeting with the IAEA; day two of the UMREG TM was held jointly and concurrently with the first day of WISSYM 2015. The aims of this TM were as those of the second UMREG meeting in Freiberg, described above. The IAEA officer responsible was P. Woods. One manuscript based on a presentation at this meeting is included in this report.

Extraction of hazardous constituents from tailings resulting from processing of high grade uranium ore

H. Jung (Germany) described a proposal to eliminate the main hazardous constituents from uranium tailings, particularly those arising from high grade uranium ore, to remove the associated risks of potential future escape of those constituents from the tailings into the environment, especially in the long term. The radiological long term safe disposal of eligible tailings would be enhanced if both radium and thorium were to be extracted and removed. The extraction of non-radioactive hazardous constituents such as the so-called heavy metals and other toxic elements would also enhance the safe disposal of tailings. The costs of de-toxifying uranium tailings, simplifying their future management, can be considered in the context of the very long term maintenance costs for tailings disposal facilities containing more toxic materials. The paper gives the justification for such treatments, and describes schemes to treat tailings from operating uranium mills prior to disposal, and for the treatment of legacy tailings before final disposal into a suitable impoundment. The potential advantages and limitations are discussed, including financial implications. An outlook to further develop the concept is given.

TECHNICAL MEETING ON PUBLIC AND COMMUNITY ACCEPTABILITY OF URANIUM MINING AND MILLING, VIENNA, AUSTRIA, 8–11 DECEMBER 2015

The need for public and community as well as governmental support — sometimes called the informal ‘social licence to operate’, or simply ‘social licence’ — associated with uranium exploration and mining projects has been recognized worldwide. The impact of negative legacies from earlier uranium mining and milling activities has long been acknowledged, especially their ability to undermine the public and community acceptability of current and proposed uranium mining projects. The need for better planning, communication, commitment and performance by uranium exploration and mining projects in this area is widely accepted.

This technical meeting brought together practitioners, technologists, environmental workers, miners, operators, researchers and regulators to exchange information and discuss approaches to current public and community acceptability issues related to uranium exploration, mining and remediation activities within the uranium production cycle.

The IAEA officer responsible was P. Woods. Six manuscripts based on presentations at this meeting are included in this report.

The evolution of stakeholder communication in Northern Australia

A presentation by P. Waggitt (Australia) described that uranium mining has been carried out in the Northern Territory of Australia more or less continuously since 1945. At the outset, involvement of and consultation with, stakeholders in general and traditional Aboriginal owners in particular was not always a major consideration and in many cases minimal at best. As the social and political scene has matured so the realization has come to all parties that inclusive stakeholder consultation, and with it the granting of the 'social licence', has become an integral part of successful and sustainable development. Indeed, without the 'social licence' new projects are unlikely to be granted regulatory approval to proceed.

This paper records some of the experiences and stages of development in the stakeholder consultation processes as related to uranium mining activities in the Northern Territory since the early days, and more especially over the past 30 years. The case studies include exploration and mining activities as well as significant remediation programmes. Finally, the paper discusses lessons learned and future plans.

Uranium — the Saskatchewan experience

K. Cunningham (Canada) outlined the experience in the Canadian province of Saskatchewan, which has hosted uranium mining following the discovery of pitchblende in the 1930s. Three eras of production are described; throughout this production history, uranium and nuclear issues have remained a contentious and controversial subject. Nevertheless, while there have been multiple political parties governing the province, support for the industry has been continuous by those parties. Uranium companies have taken a very active role in educating the public and increasing support for uranium mining and become leaders in socioeconomic benefit programs and environmental protection. The uranium industry has a high level of public acceptance as a result of government and corporate responses to issues and concerns.

Social licensing in uranium mining — between ethical dilemmas and economic risk management

W.E. Falck (France) discussed and contrasted the ethical and economic risk management aspects of mining, including uranium mining, which come at the price of environmental and social impacts. While minimizing environmental impacts with a view to comply with regulatory requirements today is a standard procedure in mine business management, this is not necessarily so the case for social impacts. On the other hand, many societies today express their desire to participate in the decision finding on the development of their physical and economic environment. A sustained and sustainable mine development requires the collaboration with the host communities concerned, which means that it has to be developed in a process commonly termed social licensing. Falck argued that a 'social license' will not be granted once and for ever, but in fact is an evolving process, as the communities and their needs evolve. This paper examines the evolution of social licensing in the context of various ethical dilemmas and divergent norm and value systems of the different actors, such as host communities, mining companies and society as a whole. It also argued to make social licensing an integral element of business (risk) management for mining companies.

Public participation and acceptability of uranium mining and milling in India — a case study

Uranium mining in India was started in 1967 by the Uranium Corporation of India Limited (UCIL) at Jaduguda in Jharkhand. R.K. Mishra (India) described recent practice; between 2003 and 2011 eleven environmental public hearings were conducted for uranium mining projects in different parts of India. While the uranium mining industry in India too faces social challenges, the public has favoured all the projects, with certain demands and concerns. The most common demands are described, and the response of the mining company. Good environmental practice and active social participation through corporate social responsibility has overcome the above challenges to make uranium mining projects of UCIL more acceptable to society.

Environmental attributes of mining and processing of uranium ore in Singhbhum, Jharkhand, India

V.N. Jha (India) presented on environmental attributes from India’s Jharkhand uranium mining district, noting that they mostly originate from nature of the deposit and its extraction. In detail, these depend on series of governing factors such as grade mined, methodology of mining, processing and waste management, climatological conditions and nature of discharges. In accordance with existing regulatory guidelines, proper management of waste is ensured to address the environmental concern during operational and/or post-operational phases. This paper summarizes the features of uranium mining, ore processing and waste management, key environmental attributes pertaining to radiological concerns, monitoring results of diverse matrices for operational facilities of Singhbhum, India and the regulatory approach employed there.

From cradle to grave: managing the consequences of failing to engage indigenous people in the whole of mining process

In this paper H. Smith (Australia) examined how indigenous engagement by Australian mining companies has evolved over the past 50 years and highlighted some of the negative consequences that can arise from ineffective cross-cultural consultation. In the paper a special focus is placed on uranium mining and milling and a specific engagement strategy for the Ranger Uranium Mine is discussed as a case study. From this, a more general strategic approach based on cultural recognition is proposed. Recent outcomes for the Ranger Uranium Mine are considered to be promising so far, but further work is required to determine if the general strategic approach will be successful.

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SELECTED PAPERS

GEOLOGY OF THE KAYELEKERA URANIUM DEPOSIT, MALAWI[4]

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Abstract

Kayelekera is a tabular sandstone-hosted deposit hosted by Permian carbonaceous and pyritic arkoses of the Karoo rift-fill sequence. With an average mined grade in excess of 800 ppm U_3O_8 (~680 ppm U) the deposit is higher in grade than most comparable deposits in the East African Karoo basins. The age of primary mineralization remains poorly constrained, but the deposit could be a product of Permian rifting. An important feature of the mineralization and which has contributed in no small part to the higher grades is overprinting by secondary processes which we infer are related to movement on NW–SE–trending Tertiary normal faults. This overprinting occurred after the arkoses had been rendered impermeable by clay cementation.

1. INTRODUCTION

The Kayelekera Project is located in northern Malawi, 52 km west of the provincial town of Karonga. Kayelekera is a sandstone-hosted uranium deposit with a pre-production resource of 19,900 tonnes of U_3O_8 (~16,900 tU) at a grade of 0.08% using a 0.03% cut-off (~0.068% U and ~0.025% U respectively). Kayelekera is one of several significant uranium deposits within Karoo-aged sandstones of eastern Africa, including Dibwe and Mutanga in Zambia, Nyota and Likuyu in Tanzania and Livingstonia in Malawi. It is, however, the only one of these deposits to have achieved production. It is the purpose of this paper to update previous descriptive papers [1–3] with new data based on recent exploration and resource drilling and several research projects undertaken in 2010 and 2011 and on evolving understanding of the regional geology. The discovery and development history of the deposit is well documented [1, 2] so this will not be repeated herein.

2. REGIONAL GEOLOGICAL SETTING

2.1. Proterozoic basement

Kayelekera is situated close to a major but little-studied tectonic boundary between two distinct Proterozoic domains, the NW–SE–trending Ubendian and the NE–SW–trending Irumide domains. It is not clear at this point whether this proximity is merely coincidence or whether it is significant in ore formation. The elongate Ubendian domain consists of medium to high grade metamorphic rocks and intrusions. In Malawi these are referred to as the Malawi Basement Complex. The Ubendian domain contains a number of major NW–SE dextral shear zones which are cut by late- to post-tectonic granitoid intrusions dated at 1.86 Ga [4]. These shear zones may well have been reactivated during and after deposition of the Karoo sequence, since many major brittle faults that offset the Karoo-aged rocks have the same orientation. Uraniferous pegmatites are known to occur within the Ubendian, and these may represent a source of uranium for Kayelekera and other deposits.

The Irumide Belt has a markedly contrasting fabric to the Ubendian and comprises a basement of deformed Lower Proterozoic crystalline rocks, unconformably overlain by a sequence of

[4] Presented at the Technical Meeting on the origin of sandstone uranium deposits: a global perspective, Vienna, Austria, 29 May–1 June 2012 (updated 2015).

shallow water quartzites and pelites known as the Muva Supergroup. Deposition of the latter has been dated at about 1.80 Ga [5]. Basement and cover were intruded by granitoids at approximately 1.60 Ga [5, 6]. The main Irumide deformation and metamorphism is believed to have peaked at about 1.0 Ga consistent with the intrusion age of synorogenic plutonic rocks [5]. The location and regional geological setting are shown in Figure 1.

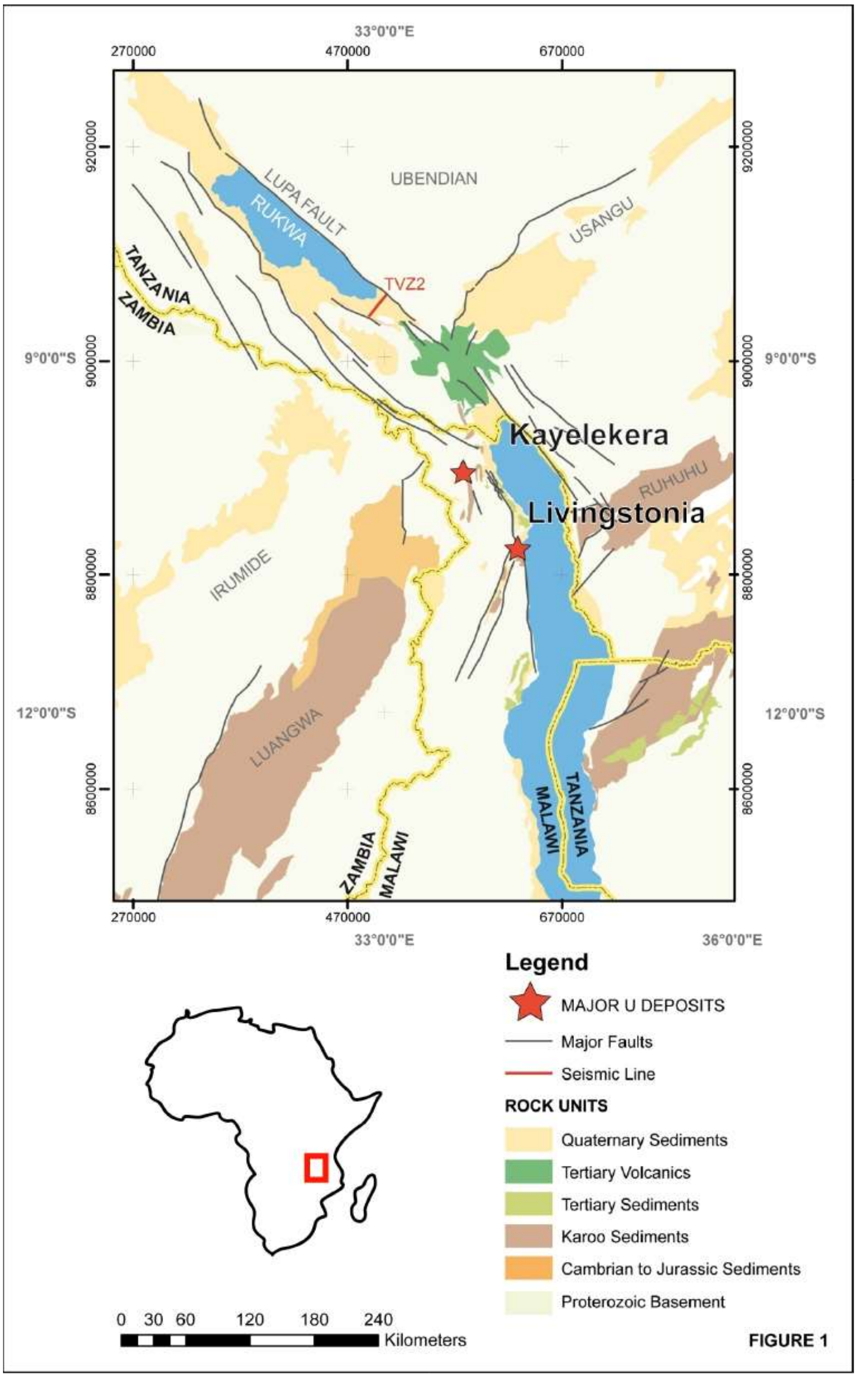

FIG. 1. Regional geological setting of the Kayelekera mine.

2.2. Unconformable Permian to Jurassic Karoo basins

A relatively flat pre-Permian topography and paucity of Upper Proterozoic and Lower Phanerozoic sediments suggests that the Ubendian/Irumide basement had been subjected to an extremely protracted period of erosion prior to the deposition of the basal units of the Karoo Basins during the Lower Permian.

Karoo basins of the Lake Malawi area have two preferred orientations, NE–SW trending such as the Selous, Ruhuhu and Luangwa basins (Fig. 1) and NNW–SSE trending exemplified by the Rukwa basin in which Karoo-aged sediments are mainly inferred from seismic data [7]. The Rukwa basin is bounded to the NE by the Lupa fault, which seismic imagery shows dips at about 45°SW and has about 1km of normal displacement [7]. This fault may be listric like other faults in the basin with similar orientations. The basin that hosts uranium mineralization at Kayelekera is the North Rukuru basin (NRB) which has a regionally anomalous north–south orientation.

The Karoo rocks in Malawi consist of basal glacial sediments and coals succeeded by ferruginous arkoses, mudstones and conglomerates. These rocks are described in more detail below. Karoo sedimentation was terminated by initiation of the Gondwana erosion cycle during the Lower Jurassic. Dolerite dykes are widespread in central Malawi and trend NNE to NE [8]. These dykes are probably a manifestation of the Lower Jurassic Karoo large igneous province recognized throughout southern Africa and dated at approximately 180 Ma [9].

2.3. Post-Karoo rocks

Post-Karoo sediments in the vicinity of Kayalekera are mainly restricted to the Rukwa rift and its southern continuation southward, under and adjacent to Lake Malawi (Fig. 1). In the Rukwa rift these rocks are assigned to the Mid Cretaceous Galula Formation, containing dinosaur fossils and presumably equivalent to the outcropping Cretaceous Dinosaur Beds of northern Malawi [10]. The Cretaceous rocks of the Rukwa rift are overlain with angular unconformity by over 300 m of the Palaeogene Nsungwe Formation [10]. The latter consists of a basal fluvial quartz–pebble conglomerate and quartz arenite and overlying alluvial fan complex.

The intersection of the NW-trending Rukwa and NE-trending Luangwa rifts is marked by an alkaline to carbonatitic Tertiary volcanic complex known as the Rungwe Volcanic Province [11]. There are many Tertiary to Recent volcanoes, typically associated with NW-trending structures. Isotopic dating of three tuffs from the Rukwa basin yielded ages of between 25.9 and 24.6 Ma [10].

3. LOCAL GEOLOGICAL SETTING

3.1. Basal beds (K1) and coal measures (K2)

The oldest sediments of the Karoo sequence of the North Rukuru Basin have been termed 'Basal Beds' [2]. The Basal Beds include glacial and glacio–lacustrine sediments (K1) namely diamictite (tillite) with overlying flaggy sandstone and varved shale beds (Fig. 2(a)). This glacial unit has been dated as Lower Permian (Sakmarian) using palynological evidence [2].

Overlying coal measures and arkose were previously included in the North Rukuru Sandstone [2] but are here assigned to K2. The base of the coal measures is defined by a cross-bedded pebbly sandstone. Individual pebbly grit beds grade into fine-grained sandstone and are separated from the next grit bed by thin layers of fine, micaceous, flaggy sandstone. This overall fining upward succession is overlain by a sequence of mudstone, carbonaceous shale and coal seams up to 1.5 m thick.

3.2. North Rukuru Sandstone (K3 to K5)

Overlying the Basal Beds with angular unconformity are arkosic sandstones and mudstones of the North Rukuru Sandstone, deposited in braided and meandering river systems [2]. Several informal units are recognized within the North Rukuru Sandstone [2]. These are the Upper Kalopa Arkose Member, Muswanga Red Bed Member and Kayelekera Member. The arkoses of the Muswanga Member are characterized by a hematitic matrix that is partially altered to goethite on weathering. A distinctive bed containing fossilized wood occurs at the top of the Muswanga Member. This bed defines the top of K3 in the Kayelekera area.

The Kayelekera Member (K4) is about 150 m thick and is the main uranium host. It is relatively well-known due to numerous drill hole intercepts and exposure in the open pit. At least 10 arkose units have been identified which range in thickness up to 14 m (Fig. 3). Each arkose is assigned a letter of the alphabet with production to date sourced mainly from the U, T and S units. Arkoses define the base of cyclothems and pass upwards into reddish to chocolate brown 'oxide facies' mudstone and then into 'reduced facies' grey-black carbonaceous and silty mudstone (Fig. 2(c)). Thin coal rich horizons are present at the top of some cyclothems. The redox interface defined by the change from oxide to reduced facies mudstone is bedding-parallel (Fig. 2(c)) and is probably indicative of fluctuations in redox potential during, or soon after, sedimentation. Several carbonaceous samples from the Kayelekera Member were dated as Middle Permian (Kazanian) using palynological evidence [2].

The arkoses contain poorly sorted clasts of subrounded to subangular microcline, perthite, plagioclase, quartz, chert, polycrystalline quartz, biotite, muscovite, mudstone pellets, cellular plant material and unidentified carbonaceous material associated with framboidal pyrite [2, 12]. Feldspars are typically pink to red, with the red coloration is interpreted to have been inherited from source [2, 12]. Carbonaceous debris occurs as fine layers, as disseminations and as individual woody fragments several centimetres in length. Discrete dark-colored layers of <1 mm thickness are defined by higher concentrations of carbonaceous material or heavy minerals such as ilmenite, zircon and rutile.

The arkoses can be classified as arkose, litharenite and Fe–sand and the mudstones as shales and Fe–shale according to the scheme of Ref. [13]. Mudstone samples have been analysed by X ray diffraction and by short wave infrared spectroscopy [12]. Both techniques confirm smectite as the dominant clay constituent together with minor kaolinite and white mica. Dominant kaolinite was found in surface and near surface samples and thus probably relates to relatively recent weathering. Little difference in mineralogy was noted between oxidized (red-brown) and reduced (grey) mudstones.

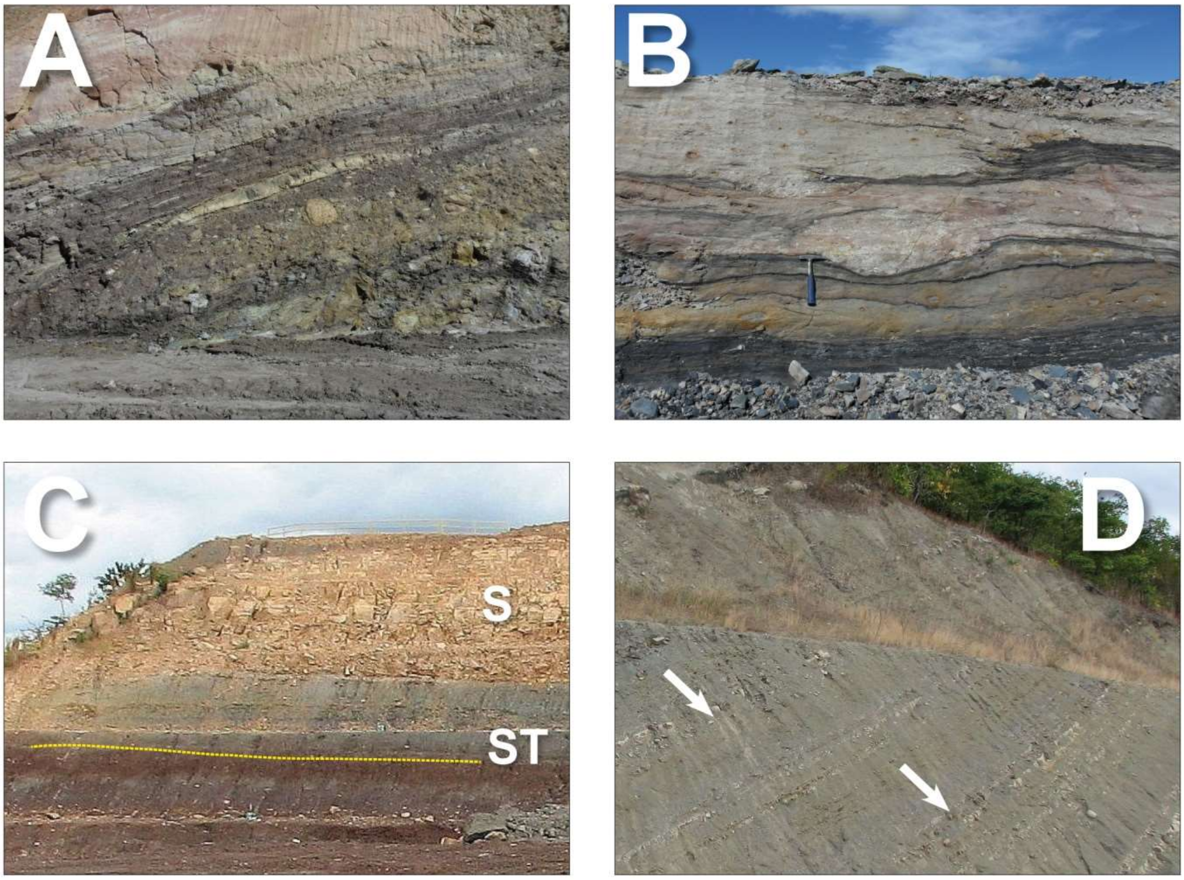

FIG 2. (a) Basal Beds (K1) near the basement unconformity along the Karonga–Chitipa road. Tillite at the base overlain by flaggy sandstone and varved shale; (b) Coal measures (K2) along the Karonga–Chitipa road. Flaggy micaceous sandstone, carbonaceous shale and coal seams; (c) S arkose and ST mudstone showing horizontal redox interface (dashed yellow line) between grey and chocolate brown mudstones. Open pit; (d) Carbonaceous mudstone; (e) Lacustrine sediments, grey–green mudstone and creamy white limestone (examples arrowed), possible lateral equivalent of K4.

A distinctive Karoo unit has in the past been assigned to K5. This unit is relatively rich in grey-green mudstone and discrete limestone beds (Fig. 2(d)). Recent mapping suggests that this is laterally equivalent to the K4 unit and represents transition from alluvial channels into a lacustrine environment.

3.3. Post–depositional history

The margins of the NRB are not well exposed, but there is little doubt that the eastern margin is defined by a major NW–SE trending fault, referred to as the Eastern Boundary Fault. The dip of this fault is poorly constrained, but is likely to be steep if not vertical, at least near the surface. Sediments of the North Rukuru Basin generally dip at 35°E. Adjacent to the fault on the eastern margin of the basin, however, the dip is often 10 to 20°W. This dip reversal has been interpreted as the result of faulting [2].

The eastern boundary fault actually consists of several fault planes, one of which is exposed in the eastern part of the pit where normal displacement is evident. The deposit occupies a syncline axial zone which is a down-faulted block bounded by NNW trending normal faults. Transverse faults with limited offset cut across this structure causing a dip reversal to the north and the creation of a basin structure bounded by faults on three sides.

The western boundary of the NRB is suggested by magnetic data to be shallower and could be a low angle fault or depositional unconformity, juxtaposing K1 glacial sediments or K2 Coal Measures against metamorphic basement rocks.

4. THE OREBODY

4.1. Distribution of ore

Ore at Kayelekera is hosted in several arkose units where they are adjacent to the Eastern Boundary Fault zone (Figs 3 and 4). The ore forms more or less tabular bodies restricted to the arkoses, except adjacent to the NS strand of the Eastern Boundary fault at the eastern extremity of the pit (Fig. 3). Here, ore also occurs in mudstones in the immediate vicinity of the fault. It can be seen that the highest grades correspond to the intersection of the eastern and Champhanji faults (Fig. 3). Ore grade and tonnage declines with lateral distance from these faults. Figure 6 presents a representative cross–section of the orebody. Secondary ore tends to be concentrated in vertical fractures and along the contacts between mudstone and arkose (Fig. 4) and is restricted to the upper parts of the orebody.

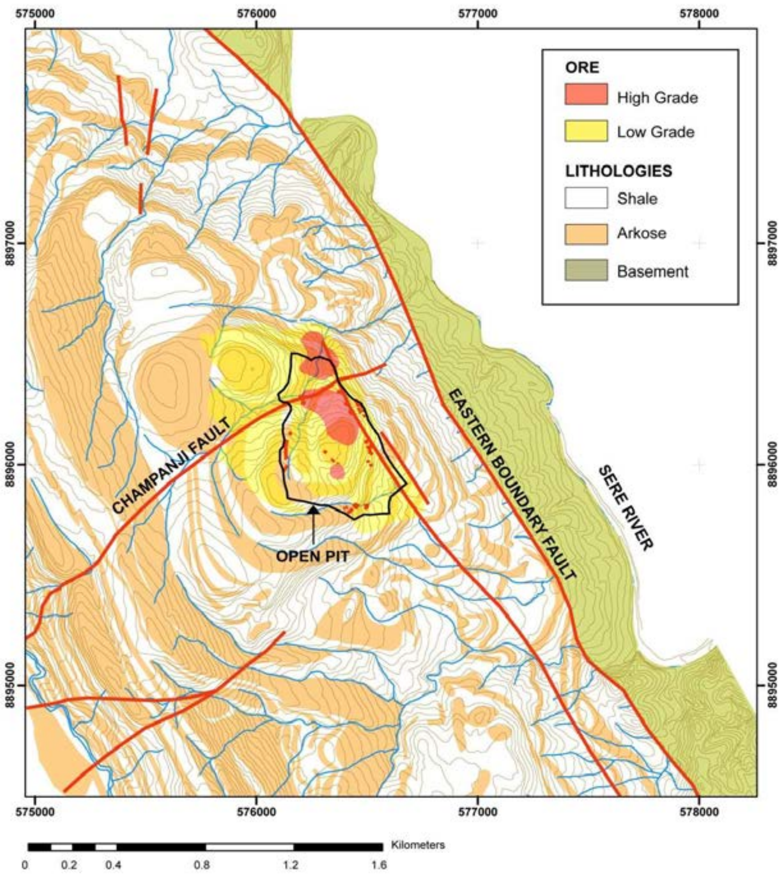

FIG. 3. Geology of the Kayelekera pit area.

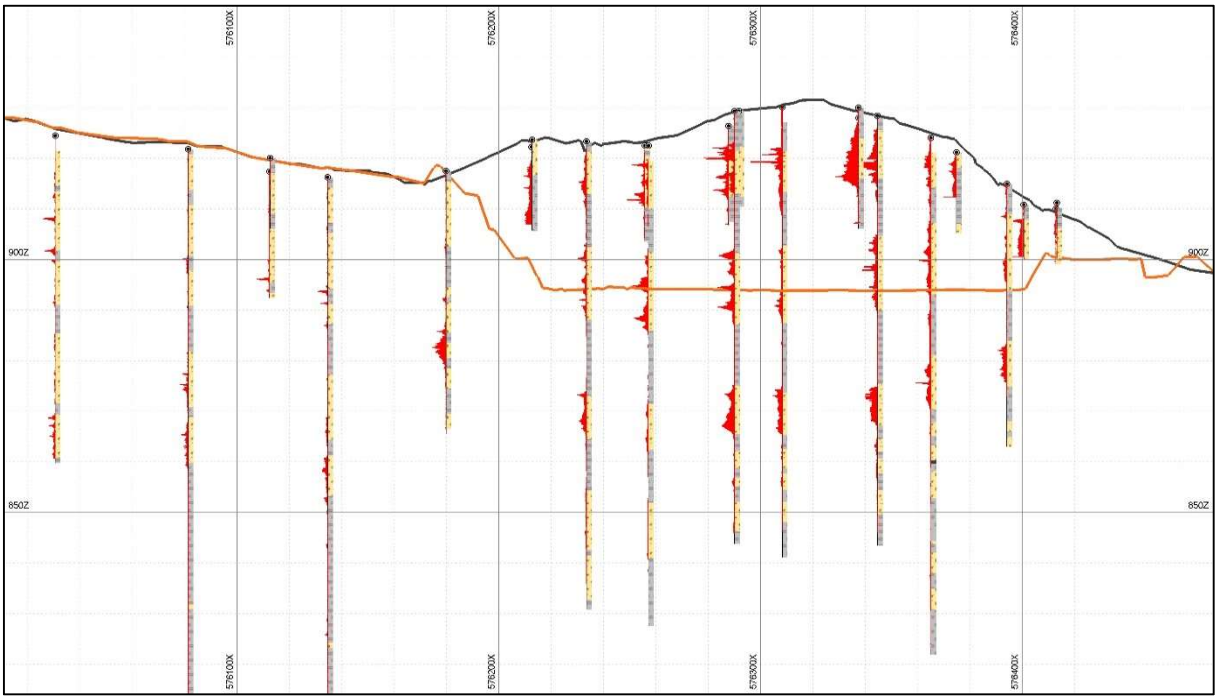

FIG. 4. Representative cross-section of the Kayelekera orebody. Yellow — arkose, grey — mudstone. Red — uranium grade. Orange line is base of pit in 2012 and the black line is the original land surface.

4.2. Ore types

Primary reduced (i.e. carbon and pyrite-bearing) arkose ore accounts for 50% of the total ore [1]. About 30% of the ore is hosted in oxidized arkose (i.e. lacking carbon and pyrite) and is called oxidized ore. The remaining 10% of ore is termed 'mixed arkose' and exhibits characteristics of both primary and secondary arkose ore types. Modal gangue mineralogy is given in Table 1.

TABLE 1. AVERAGE MODAL MINERAL CONTENT OF THREE MAIN ROCKTYPES

Mineral Wt%	Oxidized arkose	Reduced arkose	Mudstone
Quartz	37.6	46.2	6.1
Smectite	7.7	3.6	21.0
Kaolinite		2.1	1.9
Illite	2.7		18.6
Biotite		1.2	
Albite	49.4	35.9	9.2
Microcline	2.7	5.2	5.0
Calcite		5.0	1.7
Pyrite			0.3
Hematite		0.7	1.6
Amorphous			34.7

Uranium in primary ore is present as coffinite, minor uraninite and a U–Ti mineral, tentatively referred to as brannerite [14]. Uranium occurs in a variety of forms, some of which are illustrated in Figs 5(a–d). Modes of occurrence include: disseminated in matrix clay, included in detrital mica grains and intimately intergrown with carbonaceous matter. Individual grains are extremely fine, typically <10 µm. Figure 5(b) illustrates the association of uraninite with detrital zircon. Coffinite and uraninite also show an association with a TiO_2 phase, possibly rutile after detrital ilmenite. It is possible that uranium deposition was accompanied by leaching of Fe from detrital ilmenite and precipitation of a TiO_2 polymorph. Calcite is a significant component of the primary reduced ore at 5%.

Oxidized arkose is characterized by evidence of feldspar dissolution, prevalence of matrix iron oxide and consequently, red to orange–brown colour. It is readily distinguished from darker, greyish reduced arkoses. Oxidized arkose is found at or near the current surface and in peripheral parts of the deposit. Secondary uranium is often most concentrated at contacts with adjacent mudstones. Most of the uranium in these rocks is present as autunite ($Ca(UO_2)_2(PO_4)_2{\cdot}10–12H_2O$), but traces of uranophane are also present as well as minor amounts of the primary minerals. Autunite typically coats detrital quartz or feldspar grains and occurs in cavities in feldspar presumably the product of chemical dissolution (Fig. 5(f)). Quantitative XRD measurements show that the oxidized arkoses contain almost no calcite or detrital biotite and have a matrix of smectite and illite rather than smectite and kaolinite (Table 1) [14].

A further 10% of primary ore is hosted by mudstone and is termed mudstone ore. Most uranium in mudstone ore is present as coffinite with lesser uraninite in a matrix of clay minerals. Quantitative XRD measurement of a composite mudstone sample shows that the mudstone mineralogy is dominated by smectite (21%) and illite (19%), but also that a significant portion (34%) of the rock is amorphous to X rays (Table 1) [14]. Uranium phases in the mudstone include coffinite, autunite, uranophane, uraninite and brannerite, but typically fine grain size prevents unambiguous identification [15]. Figure 5(e) illustrates a typical mode of occurrence of uranium, apparently replacing matrix clay minerals and rimming detrital grains and carbonaceous fossils.

4.3. Bulk chemistry

Table 2 presents average major element analyses of various lithologies from the open pit. The three main rocktypes, sandstone, siltstone and mudstone are broken down into reduced and oxidized. The arkoses show almost no major element difference between oxidized and reduced. Furthermore, both oxidized and reduced mudstones have similar major element chemistry with the exception of iron, which is twice as abundant in the oxidized variety. Uranium correlates moderately well with total organic carbon with a coefficient of 0.6 based on 77 samples of oxidized and reduced ore. As might be expected, however, there is much less organic carbon in oxidized rocks relative to the reduced ones.

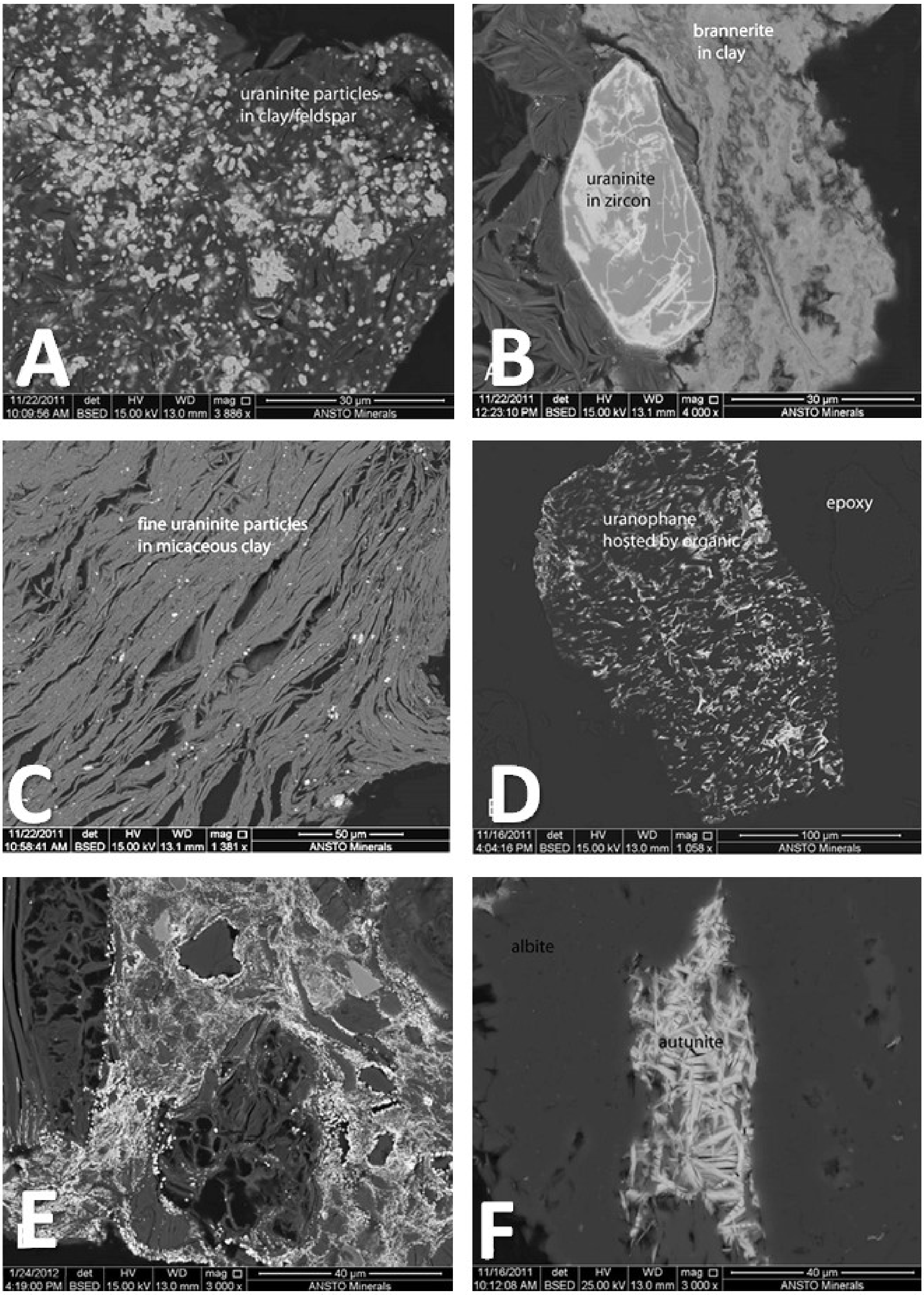

FIG. 5. Backscattered electron images illustrating modes of occurrence of uranium at Kayelekera.

TABLE 2. AVERAGE BULK CHEMICAL COMPOSITION OF MAJOR ROCKTYPES (%)

Rock type	Arkose			Siltstone		Mudstone	
	Oxidized	Reduced	Unknown	Oxidized	Reduced	Oxidize	Reduced
n	35	11	3	1	7	6	13
SiO_2	75.5	74.0	73.5	56.8	55.4	54.3	53.6
TiO_2	0.49	0.36	0.85	0.61	0.93	0.89	1.00
Al_2O_3	10.5	10.3	11.8	12.4	18.7	17.1	20.6
Fe_2O_3	3.7	4.5	3.4	11.8	5.9	10.2	5.1
MnO	0.11	0.04	0.02	1.64	0.05	0.05	0.07
MgO	0.2	0.9	0.3	0.9	1.6	1.5	1.7
CaO	0.5	0.7	0.5	0.7	1.2	0.8	0.9
Na_2O	4.1	3.7	4.3	3.6	3.3	1.0	1.4
K_2O	1.4	1.3	1.8	1.3	2.3	3.3	3.6
P_2O_5	0.13	0.15	0.05	0.05	0.08	0.09	0.10
BaO	0.11	0.36	0.06	0.39	0.07	0.06	0.07
LOI	2.55	2.67	3.10	8.10	9.55	10.36	11.98
CO_2	0.05	0.16	0.03		0.08	0.05	0.05
C_{org}	0.03	0.07	0.14	0.03	0.91	0.07	0.30
Total	99.4	99.1	99.8	98.2	100.1	99.8	100.4

A range of trace elements was analysed for. As with the major elements, the trace elements show little significant difference between mineralized and mineralized samples, uranium being the notable exception. The mudstones are generally enriched in most trace elements relative to the arkoses, including the rare earth suite. Mo is generally present at low concentration (< 10 ppm) except some examples from the reduced siltstones, which contain up to 200 ppm. Se is generally present at < 10 ppm. Modest enrichment of V (to 300 ppm) is seen in the mudstones.

A few elements display weak correlation with uranium (Pearson correlation coefficient of > 0.25) notably S (0.31), Mo (0.31), Ga (0.26) and Ni (0.26). The Mo correlation is, however, questionable due to a large number of the analyses reporting below detection limits. No other elements from a wide range analysed (66 elements) shows any correlation with uranium or notable enrichment.

4.4. Paragenesis

A complex post-depositional paragenetic evolution has been previously proposed [12]. One of the earliest events recognized under the microscope is the development of albite overgrowths on detrital feldspar and quartz overgrowths on detrital quartz. Such overgrowths are in some cases sufficiently abundant to occlude porosity. In most cases, however, primary porosity is infilled by combinations of smectite, calcite, illite, pyrite, chlorite, ferroan carbonate and iron oxide. A Na–Al silicate, 'probably zeolite' was identified in some samples [12]. Smectite also occurs as a late fracture coating. Chlorite replaces early smectite as well as detrital grains of biotite and muscovite. Calcite is locally abundant and is interpreted to replace quartz. Calcite is itself replaced by ferroan carbonate. Framboidal pyrite is associated with organic material and, in some cases, is interpreted to replace detrital quartz and feldspar.

5. DISCUSSION

5.1. Fundamental architecture

The post-Carboniferous history of Malawi is complex and poorly understood. A major rifting event was probably initiated in the early Permian, although older sediments outcrop to the north of the Luangwa basin (Fig. 1). Today several elongate and NE–SW trending basins attest to this event. It is not clear, however, whether these basins retain their original sedimentary architecture or whether they are the remnants of one or more larger and more extensive basins. Intra-formational unconformities within the Karoo sequence attest to the episodic nature of this extension. Permian rifting was probably terminated prior to the onset of the Triassic, as no rift-fill sediments of this age are known in northern Malawi. Alternatively, Triassic sediments may have been completely eroded and removed. Indeed, the red bed sandstone unit of the Rukwa Rift could be Triassic, but palynological data are needed to confirm or deny this.

5.2. Drivers of fluid flow

One of the main uncertainties of uranium deposition at Kayelekera is its age. There are currently no radiometric ages available. We hypothesize that primary ore formation occurred soon after sedimentation, in which case topographic drive related to emergence of horst–graben morphology may have been the prime driver of ore bearing fluids. The point at which porosity became occluded to its current low level is not known.

5.3. What caused uranium precipitation?

The association of primary uranium with arkoses containing presumably sedimentary carbonaceous material (up to 2.5% total organic carbon in our analyses) and diagenetic pyrite suggests the possibility that reduction of an oxidized ore forming fluid was a critical depositional mechanism. Additionally, the spatial association of uranium with TiO_2 polymorphs probably reflects oxidation of clastic ilmenite and incongruent dissolution, where iron is removed and Ti retained as anatase or brookite and/or partially dissolved to form the U–Ti mineral brannerite. Alternatively, mobile methane (or higher hydrocarbon) sourced from underlying coal may have been important.

Uranium is clearly not in a roll-front configuration, nor does it show a clear relationship with redox interfaces in pit faces. Indeed, much goethite is clearly related to late fluid movement along fractures along arkose/mudstone contacts and perpendicular to bedding. Thus, a model in which oxidized fluid migrated along an aquifer arkose precipitating uranium at a well-defined redox interface is not appropriate.

The secondary, mainly fracture-controlled ore is dominated by autunite in which uranium is probably present as both reduced and oxidized forms. The chemical depositional mechanism for this mineral is unclear.

6. CONCLUSIONS

Kayelekera is a tabular sandstone-hosted deposit hosted by Permian carbonaceous and pyritic arkoses of the Karoo rift fill sequence. The age of primary mineralization remains poorly constrained, but could be a product of Permian rifting. Many other aspects of ore deposition remain unclear, and more research is needed.

An important feature of the mineralization and which has contributed in no small part to the higher grades is overprinting by secondary processes which we infer are related to movement on NW–SE–trending Tertiary normal faults. This overprinting occurred after the arkoses had been rendered impermeable by clay cementation.

ACKNOWLEDGEMENTS

The authors acknowledge the permission of Paladin Energy to publish this manuscript and the many geologists who have contributed to the current understanding of Kayelekera geology.

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BEST PRACTICE IN ENVIRONMENTAL MANAGEMENT OF URANIUM MINING[5]

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Abstract

Over the last two or three decades, the importance of recognizing and minimizing the environmental impacts of mining and associated industries has become more accepted. The IAEA (International Atomic Energy Agency) supports good practice in the mining and extraction of uranium and thorium worldwide. Further to its well-known safety standards for radiation protection, regarding the uranium production cycle it has produced guidance and acts as a gatherer and provider of information on technological, environmental, regulatory and geological aspects. A number of Technical Cooperation projects throughout the world on this and related topics are supported. A "Best Practice in Environmental Management of Uranium Mining" document was produced in 2010; the theme is addressed by many IAEA activities.

1. INTRODUCTION

The motto of the International Atomic Energy Agency (IAEA) is "Atoms for Peace". The uranium production cycle, including exploration, mining and processing of the raw materials for nuclear power, is one of the themes where the IAEA is active in promoting best practice. This extends to the eventual decommissioning and remediation of mining and processing facilities, and where required, to the remediation of legacy sites left from earlier styles of mining.

In particular, interest and expertise in these matters at the IAEA is contained in two of its Divisions:

— Nuclear Fuel Cycle and Waste Technology Division;
— Radiation Transport and Waste Safety Division.

Other parts of the IAEA are also involved, including the Department of Safeguards (who inspect security and safeguards aspects of uranium mines on the ground, as well as their better-known work with uranium enrichment facilities and nuclear power plants), and parts of the Department of Nuclear Sciences and Applications. Each year the IAEA organizes or participates in many activities supporting the uranium production cycle [1]. Some of activities are described below.

Nearly all environmental aspects of uranium mining are also relevant for other commodities, although special emphasis is put on radiological protection in the case of uranium. At the same time, naturally occurring radioactive materials are relevant in many other industries, notably thorium and mineral sands mining and the oil and gas industry. Perhaps because of the additional factor of radiation protection, in some countries the general environmental protection requirements for uranium mining are, or were, stricter than requirements for other mining and as a result were sometimes developed earlier than for other mines. Hence guidelines prepared for uranium mining have broader application, and are worth consulting for other types of mining.

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[5] Presented at the UMREG 2012 meeting, Vienna, Austria (updated 2015).

In 2010 the IAEA published Best Practice in Environmental Management of Uranium Mining [2]. This report may be freely downloaded from the internet. This paper summarizes its content and relates it to other related activities internationally and at the IAEA.

2. OUTLINE OF BEST PRACTICE IN ENVIRONMENTAL MANAGEMENT OF URANIUM MINING

The 2010 IAEA report [2] has four sections summarized below.

2.1. Background

The first section gives the background to the applicability of best practice to uranium mining. By identifying, understanding, managing and minimizing potential adverse impacts, key benefits are:

- Improved environmental management;
- Improved socioeconomic outcomes;
- Demonstrated good corporate governance and accountability;
- Improved liability management;
- Improved quality control;
- Reduced operational costs and increased profitability.

2.2. Guiding principles

The basic guiding principles are based on those of sustainable development. Specifically, at least the following three should be considered:

- Sustainable development;
- The ALARA principle;
- Precautionary principle.

The concept of Sustainable Development is based on the definition provided in the Brundtland Report [3], i.e. meeting the needs of the present without compromising the ability of future generations to meet their own needs. It involves balancing environmental, social, economic and governance issues.

The ALARA principle was originally developed for worker radiation protection, where risks are kept as as low as reasonably achievable with social and economic factors being taken into account. There are both guidelines and upper limits of radiation exposure for workers.

While not specifically stated in [2], environmental and other impacts could also be considered under the ALARA principle. As with radiation protection, this does not mandate zero impacts or necessarily those as low as technologically achievable with an unlimited budget. Again, there should be consideration of social, economic and governance issues and actual risks and benefits. The local setting is important; the location, climate and factors such as proximity to human populations, forests, farms or pastoral enterprises, water supplies, the condition and uniqueness or ubiquity of the local environment, and possibly many other aspects.

There have been many attempts to define the Precautionary Principle; in a simple form, it involves the anticipation, prevention and correction of the causes of environmental degradation, where the lack of full scientific certainty should not be used to postpone preventative measures if a significant risk of material damage exists. As with the other principles, the local setting and social, economic and governance issues should also be taken into account.

2.3. Best practice application

The application of best practice principles for a project begins at the conceptual phase and continues through all of the stages of the project. For modern mining, the phases are typically:

- Exploration/conceptual design;
- Feasibility studies;
- Construction;
- Operation;
- Remediation;
- Closure and post-closure stewardship.

It should be recognized that some mines may have long or short periods of time between these phases, or may cease operations for months or even years at times before re-opening. Practical aspects include:

- Exploration/conceptual design:
  - Baseline data collection, environmental and socioeconomic;
- Public/stakeholder involvement:
  - Identification of relevant people and organizations including government at all relevant levels;
  - Preparedness of the project owners, private or government, to listen to the issues raised and genuinely seek to address them.

While this last aspect takes time and effort, there are many cases where a technically, economically and even environmentally sound project has failed to get started or has suffered major difficulties or even closure due to lack of appropriate stakeholder involvement and support.

Associated with public and stakeholder involvement is typically an impact assessment stage. In this, the hazards and risks associated with a project are studied, understood and assessed. If the expected impacts are understood and acceptable with appropriate management, that aspect is considered acceptable. If the hazard and risks of an aspect of a project are not acceptable, the design or the management procedures should be modified to reduce the impact to something that is acceptable.

All of these aspects form part of a project's public and community acceptability, sometimes called 'social license to operate' (a conceptual 'license', not a formal document); i.e. its overall acceptance by the public, especially those living nearby and other stakeholders, that it is a worthwhile project and should proceed (or continue).

Before a project is constructed, plans should be prepared for normal operations including waste management and monitoring. Contingency and emergency response plans should also be prepared that can be utilized in the case of unforeseen events, including if impacts to workers, the public or the environment become or are becoming unacceptable.

Note that environmental or health monitoring in itself is not environmental or health protection. Rather, it informs the operator and stakeholders of the status of the environment and health, and any trends that may be occurring. If problems occur, action should be taken; further monitoring will confirm if conditions are returning to an acceptable state or if additional action is required.

3. OTHER RELEVANT IAEA ACTIVITIES AND PUBLICATIONS

3.1. General information

The IAEA provides a large amount of information relevant to radiation protection in all mining, oil and gas and related industries. These are organized in a hierarchy. The Basic Safety Standard [4] is the lead publication and is available in all official IAEA languages. It was last revised in 2011 following extensive consultation across the world.

Other types of publications that include material relevant to mining are:

- Safety Series;
- Safety Standards Series;
- Safety Reports Series;
- Technical Reports Series (including the Nuclear Energy Series);
- TECDOC Series (Technical Documents);
- Training Course Series;
- Proceedings Series.

Earlier publications regarding general environmental and social aspects of uranium mining include:

- Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development [5];
- Guidebook on Environmental Impact Assessment for In Situ Leach Mining Projects [6];
- Guidebook on Good Practice in the Management of Uranium Mining and Mill Operations and the Preparation for their Closure [7];
- Environmental Impact Assessment for Uranium Mine, Mill and In Situ Leach Projects [8];
- Guidebook on the Development of Regulations for Uranium Deposit Development and Production [9].

The IAEA has also organized a number of relevant conferences and open technical meetings over the last three decades that include the subject. It has undertaken and continues to undertake many Technical Cooperation projects in developing Member States, including projects regarding uranium mining and legacy site remediation.

Information exchanges using the modern medium of the internet are also hosted by the IAEA. One relevant forum is ENVIRONET, which aims to provide support and information exchange related to environmental management and remediation of radiologically contaminated sites including mines [10][6]. ENVIRONET also maintains a 'LinkedIn' account.

3.2. IAEA symposia and meeting proceedings

The IAEA has published a large number of relevant proceedings from symposia, conferences and technical meetings. Of particular interest to the UMREG (Uranium Mining and

[6] See also http://www.iaea.org/OurWork/ST/NE/NEFW/WTS-Networks/ENVIRONET/overview.html

Remediation Exchange) community are the URAM international symposium series and UMREG selected papers:

- International Symposium on Uranium Production and Raw Materials for the Nuclear Fuel Cycle: supply and demand, economics, the environment and energy security (URAM–2005) [11];
- International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM–2009 and URAM–2014) [12, 13];
- The Uranium Mining Remediation Exchange Group (UMREG) Selected Papers 1995–2007 [14].

This is just a selection and an extensive collection is downloadable from the IAEA web site.

4. OTHER GUIDANCE

4.1. World Nuclear Association

The World Nuclear Association is an international organization that promotes nuclear energy and supports the many companies that comprise the global nuclear industry. It developed from the Uranium Institute, established in London in 1975. As of early 2015, WNA stated that its current members were responsible for virtually all of world uranium, conversion, and enrichment production and most of the world's nuclear-generated electricity [15].

The WNA launched a policy document “Sustaining Global Best Practices in Uranium Mining and Processing, Principles for Managing Radiation, Health and Safety, Waste and Environment” in 2008 [16]. This publication was an outgrowth of an IAEA cooperation project that closely involved industry and governmental experts in uranium mining from around the world [17], and whose principles are in general supported by the IAEA. The WNA policy refers to the WNA Charter of Ethics, required of its members and its Principles of Uranium Stewardship.

4.2. Nuclear Energy Association

In 2014 the Organisation for Economic Co-operation and Development–Nuclear Energy Association (OECD–NEA) released its “Managing Environmental and Health Impacts in Uranium Mining” report [18]. It emerged from the consideration that public perception issues, based on serious legacy impacts, continue to delay resource and mine development in several countries. This is despite the fact that uranium mining practices have evolved considerably since the mid-20th century when most legacy sites were created. The report outlines how mining has evolved to effectively manage impacts, with case studies contrasting old and new practices and outcomes. It was developed for public consultation processes, deliberately using non-technical, plain language.

4.3. Examples of national and state/provincial guidelines (uranium mining)

National guidelines and regulations regarding responsible uranium exploration and mining exist in various forms and degrees of maturity in established uranium mining countries. Examples here are from Australia, Canada and Namibia.

4.3.1. Australia

Australia is currently the third ranked global producer of uranium and has a history of extensive investigations and regulation of uranium mining since the 1970s. General guides have been available at a national level from government (specific to in situ recovery uranium mining [19]) and industry organizational levels [20], and similar guidance (for mining in general) is available from most states. Following the lifting of government restrictions, general guidelines specific to uranium were issued by the Queensland [21] and Western Australian [22] state governments in anticipation of future uranium mine approval applications. In New South Wales uranium mining has been banned for some time but exploration has been allowed since 2012 under guidelines [23]. The current situation in the Northern Territory is described by Waggitt [24] and a recent industry perceptive on the situation in South Australia by Eckermann [25]. More generalized mining guidelines are available in the various Australian states, and individual guidelines are prepared for projects that require formal environmental impact assessment.

4.3.2. Canada

Canada is currently the second largest producer of uranium globally, and has previously held the leading position. Regulations and environmental protection measures have been well developed in recent decades. The Canadian Nuclear Safety Commission provides a standard and guidance on developing environmental protection policies, programmes and procedures at uranium mines and mills (together with other nuclear facilities) [26–28], while “[e]ach province or territory is responsible for regulating and monitoring exploration activities within its jurisdiction, and for informing the public about them” [29]. A national standard for environmental monitoring programs was produced [30]. Guidelines may be set for individual projects during the proposal stage and regulations may be customized for each uranium mine or uranium mine extension, using a risk-based approach [31].

4.3.3. Namibia

Uranium mining has a long history in Namibia, although for many years represented only by the large Rössing open cut mine. In more recent times the industry has expanded there, and it has ranked 4 or 5 for global production in recent years. The Namibian Uranium Association (previously the Uranium Institute of Namibia), part of the local Chamber of Mines, promulgates a Standard of Good Practice for Health, Environment and Radiation Safety and Security (HERSS Standard, current version dated 2014 [32]) that is to be adhered to by its members, as well as providing training courses in the field. The HERSS standards are intended to provide [33]:

1) A framework for management of health, environment, radiation safety and security in the Namibian uranium industry;
2) A reference point against which continuous quality improvement in healthcare, environmental management, radiation safety and security can take place.

The development of the HERSS Standards is promoted as an important step forward to help bring about substantial convergence between Namibian and international standards [34, 35].

4.4. Discussion

The circumstances of every individual mining and associated industry project should be considered. The geographical, political, social, climatic and ecological location of each project are all important, as are the regulatory requirements, economics of the mine, socioeconomic circumstances and local and national populations, and importantly the hazards and risks expected or possible from the industry's development or ongoing operation.

Nevertheless, international guidance is worth consulting by both miners and regulators, as well as local guidelines and regulations where they exist. With modern communications, the international interest of social and environmental non-governmental organizations is likely for any significant project. Their opinions and resources may well be sought by, or brought to, local and national interest groups. The opinions of local peoples and international groups are no longer a consideration only in developed countries, but are becoming more relevant throughout the world.

5. COMMON THEMES, DISCUSSION AND CONCLUSIONS

Some common themes emerging concerning good practice regarding environmental and social aspects of mining and minerals projects, including uranium, are:

- Consider environmental and social aspect from the earliest exploration and planning stages;
- Involve the government and the public, especially people living nearby;
- A clear, fair, independent and transparent regulatory environment is necessary;
- Consider local and international general and specific guidelines and regulations;
- Always consider the local and national circumstances of each project;
- Consider desired outcomes when undertaking regulated actions or implementing standards;
- From the beginning properly plan, account for and finance mine closure;
- Do progressive rehabilitation if at all possible, and use its results to improve rehabilitation practices.

Radiation protection is not just relevant to uranium and thorium mining, but also to mineral sands, oil and gas and other projects where uranium, thorium and their radioactive decay products are present at sub-economic concentrations. This can also include, but is not restricted to, copper, phosphate, rare earth elements and coal deposits.

Environmental and social considerations are key aspects of mining projects, from early exploration through feasibility, operation and closure. They are not the only aspects; without an orebody, suitable and affordable mining and processing methods, markets and financing, there can similarly be no successful mining [36]. All feasibility, mining and indeed closure activities at a mining project require a large number of skills and specialities, which have to be balanced. Geologists, mining engineers, metallurgists, financial and senior management all need to have an appreciation of the importance of the environmental and social aspects of their project. Similarly, the most effective environmental and social engagement specialists need to have an appreciation of the practical and economic aspects of those projects. Only then can a good balance be achieved, and the project given the best chance of 'triple bottom line' (social, environmental, economic) success.

The IAEA will continue to promote good practice in all stages of the uranium production cycle. However, it is the industry and its regulators who must take the lead role to enable the mining, oil and gas industries to supply the world with its raw materials, and most of its energy, or face ongoing, justified and sometimes project-stopping opposition from the society it exists to support.

ACKNOWLEDGEMENTS

The IAEA's Best Practice in Environmental Management of Uranium Mining report was the outcome of a technical meeting and four associated consultants' meetings. The responsible Technical Officer for that publication was P. Waggitt of the Division of Nuclear Fuel Cycle and Waste Technology.

Many other sources have been useful in compiling this paper and every attempt has been made to properly acknowledge those sources. The selection is necessarily not comprehensive, as a huge amount of information and opinion is available. My colleagues at and through the IAEA, both current and past, staff and consultants, have assisted greatly; however, the selection of cited source documents, and the opinions expressed here, are my own and may not be official IAEA policy. Many of these ideas have appeared in earlier publications but have been specifically compiled and adapted for this paper.

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REMEDIATION OF URANIUM MINING AND MILLING LEGACIES AT THE MAILUU SUU SITE (KYRGYZSTAN) — ACHIEVEMENTS AND LESSONS LEARNED DURING IMPLEMENTATION OF THE 'DISASTER AND HAZARD MITIGATION PROJECT' 2005–2012[8]

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Abstract

Remediation measures at the former mining and processing site of Mailuu Suu (Kyrgyzstan) under the "Disaster Hazard Management Project" of the World Bank are the first large scale works that have successfully been implemented at Central Asian uranium legacy sites. This paper summarizes the approach to justification and optimization of the environmental remediation strategy at the Mailuu Suu, financial and timing constraints, the various remedial measures that have been implemented to date, and lessons learned that may inform the way forward at this and other legacy sites in Central Asia. The paper provides an overview of temporary and sustainable remediation works. The relocation of the geotechnically unstable tailings facility TP 3 to a new site with long term stability (TP 6) is described in more detail, and illustrates the methodological, technical and stakeholder related challenges. The key role of stakeholder involvement, trust building and communication at all stages of the conceptual preparation, planning and implementation of the remediation measures is addressed. The paper also provides useful lessons that were learned in relation to temporary stabilization works that could not be followed up with more sustainable measures due to administrative and financial constraints.

1. 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 at an altitude between 900 and 1000 m asl. The Mailuu Suu River reports to the Syr Darya River which discharges to Lake Aral. The border with the Republic of Uzbekistan is within a distance of around 25 km. Today, approximately 25 000 inhabitants live in Mailuu Suu, a town that has seen a serious decline in living standard since the end of uranium mining that had lasted from the late 1940s to the 1960s.

As a result of uranium mining and processing, 13 waste dumps and 23 tailings ponds are scattered in the valleys of the Mailuu Suu River and its tributaries Kara Agach, Kulmen Sai und Aylampa Sai (see Fig. 1). The wastes are subject to erosion, especially during snowmelt and heavy rains, landslides, mudflows and seismic events.

[8] Paper first presented at the Technical Meeting of the UMREG in Vienna, Austria, November 2012 (updated 2015).

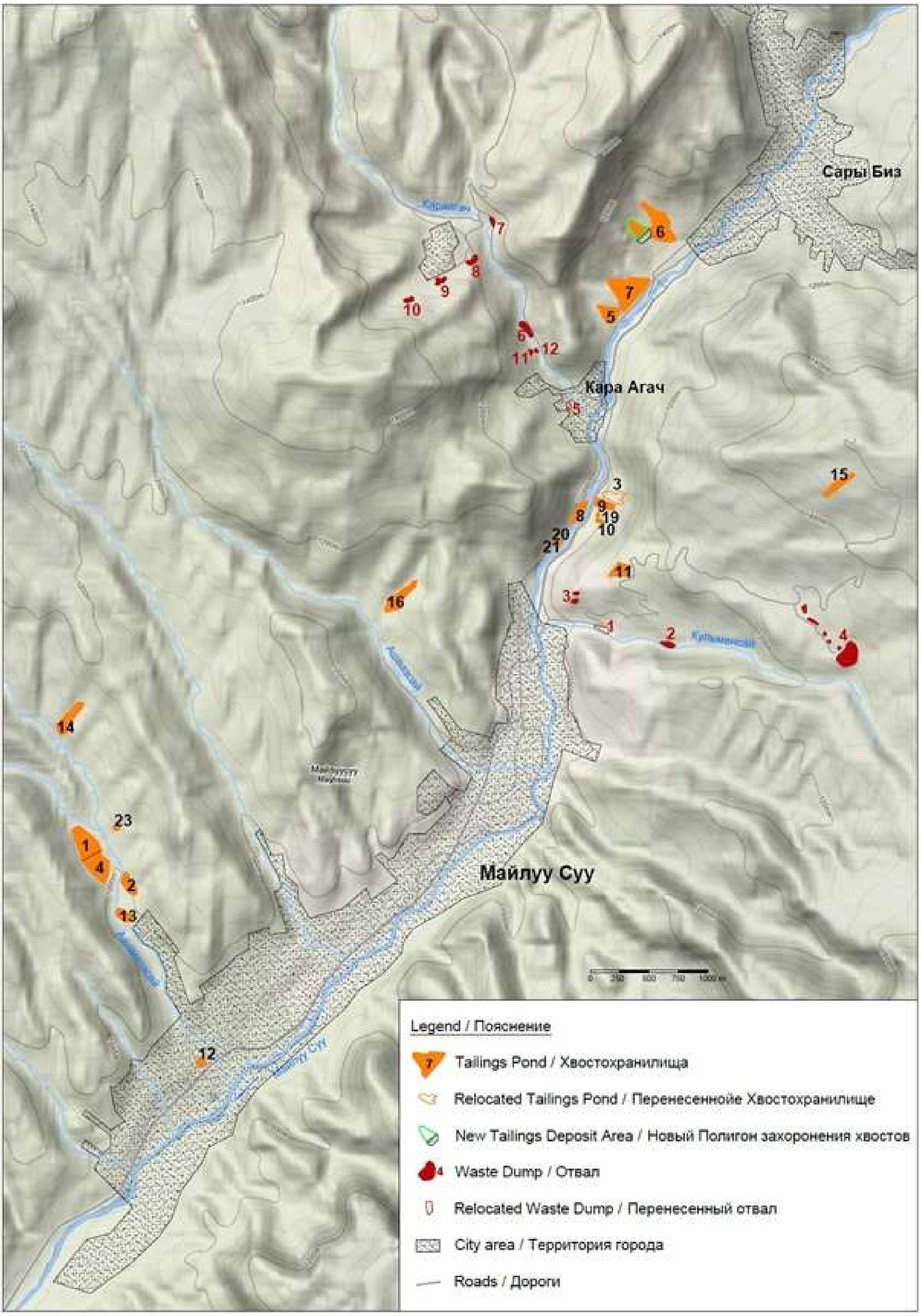

FIG. 1. Location of the waste objects.

The uranium mining legacy, and in particular the radioactive wastes that were left behind, have attracted international attention for many years. Rather alarmist news reports about what was called one of the "world's 10 most polluted sites" [1] "threatening the drinking water supply of millions" [2], their scientific validity notwithstanding, have helped mobilize funding for many national and international projects. Since the mid-1990s, several initiatives have been launched to investigate the environmental and health impacts of the wastes and propose remediation measures. Most notably the TACIS program funded by the European Commission [3] and the Disaster Hazard Mitigation Program (DHMP) funded by the International Development Agency (IDA) of the World Bank Group, but also other donors such as some western governments [4, 5] have greatly contributed to a better understanding of the environmental and radiological situation at Mailuu Suu. Under the DHMP, remediation works at waste facilities of highest priority were finally implemented.

The authors of this paper have been involved in the IDA funded DHMP, Component A, from 2005 through 2012, as part of the JV Geoconsult–WISUTEC ('the contractor' in the following). This paper summarizes the activities of the contractor during the conceptual planning and engineering design stage and focuses on the remediation works that were finally implemented. As the remediation measures under the DHMP are, to the authors' knowledge, the first physical remedial works at uranium legacy of significant scale in Central Asia (apart from minor works carried out at Kaji Sai, that have rapidly deteriorated since completion in mid-2000s), it is worthwhile to take stock of the achievements, lessons learned and challenges that have remained since the DHMP was finished in 2012. This paper builds upon a series of publications devoted to Mailuu Suu and other uranium legacy sites in Central Asia and the former Soviet Union [6–9], where further details on the site can be found that are omitted here for the sake of brevity. Other valuable sources of the historic background information of Mailuu Suu and site description include [10, 4].

The purpose of this paper is to describe the approach to justification and optimization of the environmental remediation strategy, financial and timing constraints, remedial measures implemented to date, and lessons learned that may inform the way forward at the Mailuu Suu site.

The remaining sections of this paper are structured as follows:

- Section 2 provides a brief summary of the various legacy waste facilities at Mailuu Suu;
- Section 3 describes the results of the risk analysis for the waste facilities and the resulting justification and prioritization of remediation measures;
- Section 4 describes the remedial measures that were implemented under the DHMP. While Section 4.1 summarizes the temporary works and quick fixes that could be carried out in a short time and with limited budget, Section 4.2 describes the optimization process to develop sustainable removal of the geotechnical risks associated with TP 3, whereas Section 4.3 summarizes the radiological impacts of the remediation works completed under the DHMP;
- Section 5 recaps the stakeholder engagement strategy and specific measures of communication, trust building, know-how transfer and capacity building that have proven very helpful in the implementation of the works;
- Section 6 finally summarizes the lessons learned and provides an outlook to future activities necessary at Mailuu Suu to arrive at a truly sustainable solution.

The relocation of tailings pond #3 (TP 3) to a safer disposal site (TP 6) was the most challenging part of the DMHP, both at the conceptual and engineering stage perspective and from an implementation perspective. Therefore, this aspect is discussed in more detail in this paper than other measures at other waste objects.

2. BRIEF CHARACTERIZATION OF THE WASTE FACILITIES

As can be seen from Fig. 1, waste rock dumps (WD in the following) and tailings management facilities ('tailings ponds' or TP in the following) are scattered over a large area along the Mailuu Suu River and its tributary valleys. References [10, 11] contain details of the footprint, volume and, where available, chemical, radiological and geotechnical of the tailings and waste rock facilities that are not repeated here for the sake of brevity. 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 disperses 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 (e.g. from TP 3) into the hydrological system after sudden dam failure.

It is worth noting that the tailings and waste rock dumps are of very diverse size, ranging from 900 m² and 4500 m³ (TP 20) to 10 ha and 600 000 m³ (TP 7). TP 3 that has attracted most attention from a risk assessment perspective and is discussed separately below (Sections 4.2 and 4.3) covered an area of 1.3 ha and contained a total volume of approximately 156 000 m³. Based on shear vane investigations the 43 000 m³ were tailings, the balance including a soil cover, starter and the main dam, buttress debris and alluvial material resulting from erosion of the slopes in the hinterland.

Note that some of the waste facilities were not discernible at all, such as TP 18 that is supposed to be close to TP 3 but whose existence could not be identified visually nor by radioactivity surveys. This highlights the more general problem of missing records that would allow a historic site characterization.

According to [10], the specific activity of Ra–226 in tailings at Mailuu Suu ranges from 1.1 to 27.3 Bq/g. Radioanalytical investigations of TP 3 by the contractor under the DHMP have revealed a specific activity of approximately 35 Bq/g (Ra–226) and 2.9 Bq/g (U–238), respectively [12]. Radiochemical analyses by the contractor have also shown that nuclides of the Th–232 decay series can safely be neglected in the radiological dose and risk assessment.

It should also be noted that the uranium mining legacy also comprises underground mine workings. However, only scarce information is available, and they have been excluded from the scope of work of the contractor as well as from most other projects implemented at Mailuu Suu. Therefore, they are not considered here.

3. JUSTIFICATION, OPTIMIZATION AND PRIORITIZATION OF REMEDIAL MEASURES

Justification and optimization are fundamental principles of radiation protection, together with dose limitation. In order to decide whether remedial action is justified, an exposure estimate is usually carried out, and in case the estimated effective dose of the population exceeds a reference level, remedial measures are considered justified from a radiological point of view. An effective dose of 1 mSv/a in addition to the regional natural background is internationally accepted as a reference value for remediation at uranium production legacy sites [13]. However, the need for remedial measures is not only governed by radiological conditions at a site. Protection of water resources under toxicological aspects, geotechnical hazards or development plans for contaminated land can also constitute reasons for remedial action. Note that the associated decision processes are always site specific.

Detailed investigations of the environmental and radiological situation at the Mailuu Suu legacy site were firstly carried out by Vandenhove et al. [10] using funding from the EU TACIS program, followed by dose and risk assessments by the authors of this paper under the DHMP project [11, 12]. Further investigations with a focus on water supply to the local population were carried out by BGR [4] and Corcho–Alvarado [5]. The results of all these studies can be summarized as follows:

1) Apart from one waste dump (WD 5, reportedly consisting of unprocessed low-grade ore) and some isolated radiation hot spots due to damaged or incomplete covers, no waste sites were identified which lead to an acute radiological risk to the public that would justify remediation from a radiological point of view. WD 5 was an exception as a residential house was built on its plateau, leading to effective doses clearly exceeding the 1 mSv/a reference value;
2) Dust and external (gamma) radiation did not significantly contribute to the effective dose of the population due to the fact that tailings ponds are mostly covered. Gamma exposure from uncovered waste rock piles was not critical either due to the remote location of the dumps and dose rates smaller than 1 μSv/h;
3) Only small increases of uranium concentrations were temporarily observable in the Mailuu Suu River (below 10 μg/l), which is not critical both from a radiological and toxicological point of view. BGR estimated release rates of solute uranium in the order of a few 100 g/d, which would lead to an increase of the uranium concentration in the Mailuu Suu River in the order of 1 μg/l. Likewise, the incremental activity concentrations of other natural radionuclides did not lead to noticeable effective doses [12]. In some tributaries such as the Kulmen Sai creek, concentrations may be higher [4], but due to the lack of realistic exposure scenarios this could not justify remediation. Investigations of the central water supply to the population of Mailuu Suu have shown that the central drinking water distribution system is safe but monitoring will need to continue [5];
4) The most obvious and severe impact of radioactive waste facilities is erosion of tailings and waste rock located on the banks of the Mailuu Suu River and its tributaries. While the resulting effective doses are again small and would not provide justification from a radiation protection point of view, erosion of mine wastes is not considered good practice and concerns over uncontrolled water-borne dispersal of contamination to neighboring Uzbekistan may lead to concerns over transboundary impacts;
5) In general, landslides and mudflows were identified as potential hazards for the site in that they may block riverbeds and/or impact the health and property of the population. Some waste rock dumps (e.g., WD 1 located on the steep banks of the Kulmen Say River) were identified as potentially subject to mudflows. Again, radiation doses would be negligible due to the strong dilution of any contamination originating from these dumps;
6) A major hazard was the seismic instability of the tailings pond TP 3, located in the Mailuu Suu River valley. The tailings of TP 3 comprise a significant radioactive inventory among all legacy waste sites of Mailuu Suu, and failure of the containment would have caused the sudden release of radioactive tailings into the Mailuu Suu River, potentially leading to transboundary impacts. Concerns were also raised that mobilization of the so-called 'Tektonik' landslide from the slopes behind TP 3 could threaten the stability of the entire structure. The actual impacts of a tailings release were difficult to quantify and obviously would depend on the exact failure and release mechanisms. However, the possibility of this scenario made remediation of TP 3 a priority of the DHMP.

Based on the findings on environmental impacts and existing risks, the contractor categorized the 13 waste dumps and 23 tailings facilities into one of the following groups:

1) No action required;
2) Remediation measures are recommended, but are of lower priority and may well be implemented when sufficient funding is available;
3) Intervention measures should (and can) be carried out quickly, requiring a relatively small budget, such as fencing or placing a simple cover on isolated radiation hot spots;
4) Temporary stabilization measures, mainly riverbank strengthening in river sections with strong erosion, 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.

For waste facilities in groups 3 through 5, remediation options were conceptually developed and a preferred option selected in an optimization procedure. In applying the ALARA principle, i.e., keeping radiation exposures "as low as reasonably achievable, economic and social factors being taken into account" [14], the following decision criteria were used. Note that some of the criteria are typically conflicting:

— Cost and funding constraints;
— Technical feasibility and available infrastructure;
— Environmental, social and radiological impacts;
— Time required for implementation;
— Effectiveness in reducing or removing the hazard;
— Stakeholder preferences and public acceptance.

A major constraint imposed on the decision process by the funding agency (IDA, World Bank Group) were the limited time available for implementation of the remedial measures under the project (funding was available by the end of 2012) and the indicative upper limit of implementation costs of approximately US$ 8.5 million [15] for all remediation activities.

Table 1 summarizes the remediation measures that were proposed in the feasibility phase of the DHMP by the contractor [11].

In summary, the only waste facility where radiological considerations provided sufficient justification for remedial action was WD 5. For all other objects where remediation was recommended, this was justified by insufficient geotechnical stability and the risk of damage to containment structures with subsequent release of contaminated material and/or waterborne erosion and dispersion of wastes and associated potential transboundary issues with neighboring Uzbekistan.

TABLE 1. PROPOSED REMEDIATION MEASURES AND PRIORITY RANKING

Waste facility	Impact, hazard	Proposed remediation solution
TP 3 (left bank of Mailuu Suu River)	Risk of serious damage by Tektonik Landslide, HIGH PRIORITY	Relocation to a safer location
TP 8 (right bank of Mailuu Suu River)	Strong erosion	
D 12 and 7 (Kara Agach Sai)	Strong erosion	
TP 2 and 13 (Aylampa Sai)	Strong erosion, TEMPORARY MEASURES REQUIRED	
WD 5 (Kara Agach town)	Radon and radiation risk to people due to horticultural usage of dump plateau, HIGH PRIORITY	
WD 1, 2 (Kulmen Sai)	Strong erosion	Relocation of WD 1 onto WD 2, reshaping and riverbank strengthening Potentially relocation of the WD1/2 complex to a safer site at a later stage
WD 6 (Kara Agach Sai)	Strong erosion, HIGH PRIORITY	Riverbank strengthening
TP 1, 4, 14, 20–23 (Aylampa Sai)	Strong erosion, possibly geotechnical instability	Riverbank strengthening, TP14: Repair of drainage ditches, removal of supernatant water pond recommended
TP 5 and 7 (right bank of the Mailuu Suu River)	Erosion of dam toe during flood events and damming of the Mailuu Suu River	Buttressing of dam toes, soil cover on gamma radiation hot spots
WD 11 (Kara Agach Sai)	Exposed waste rock with a high gamma dose rate	Placement of soil cover (quick fix)

4. DESIGN, IMPLEMENTATION AND SUSTAINABILITY OF REMEDIATION MEASURES

4.1. Temporary measures and ‘quick fixes’

Based on the assessment of the geotechnical and erosion risks and under the strong expectation of local authorities and the public to commence with visible physical remediation activities, for the following measures engineering designs were developed by the contractor, and environmental/radiation safety permits obtained from the competent authorities, after undergoing the state review procedure (‘State Ecological Expertise’) according to the Kyrgyz legislative framework. These measures were engineered and implemented while more complex investigation, engineering and design works were ongoing at TP 3 (see Section 4.2 below).

4.1.1. *Aylyampa Sai Rive protection embankment at TP 2 and 13*

The main purpose of the Project was to mitigate the risk of tailings erosion from TP 2 and 13 in future flood events of the Aylyampa Sai River (a serious flood event had occurred in June 2005). Gabions and similar protective structures were installed along the tailings reaching into the Aylampa Sai River over a length of several kilometers. These measures were designed as temporary and clearly communicated as such to stakeholders. Predictably, they have partly been destroyed in the meantime and indicate that sustainable solutions are required in the near future to stop tailings erosion for good.

4.1.2. *Relocation of WD 1 to WD 2*

WD 1 with a volume of 148 000 m³ was located on a hill slope on the right river bank of the Kulmen Sai River. The wastes with a steep slope were not covered or vegetated. WD 2 is located on the left embankment, upstream of WD 1. In 2005 it was partially covered by an inert soil layer with some grass vegetation. Part of the slopes of both waste rock dumps was impacted by landslides, and the toe was eroded by the Kulmen Sai River. In order to stop further hydraulic erosion of the waste rock material, it was decided in 2006 to realign the Kulmen Sai River by a new erosion-resistant riverbed over a total length of 350 m, with sufficient hydraulic capacity and additional erosion protection by installing 1430 m³ of gabions along WD 2. Realignment was finished in 2008. Subsequently, WD 1 was relocated onto WD 2 so that the length of waste material exposed to the Kulmen Sai River was further reduced.

4.1.3. *Protection of WD 6*

WD 6 on the left bank of the Kara Agach River was partly covered by grass. However, exposed and very steep parts of the slope reaching into the river bed were subject to erosion and therefore geotechnically highly instable. As rapid, but clearly temporary, mitigation action, the riverside slope of WD 6 was flattened and gabion mattresses (covering 7600 m²) as well as 1,880 m³ of riprap were placed in 2007. The gabions have been largely remained intact as of 2012 when the contractor visited the site. However, it was repeatedly pointed out by the contractor that continuous inspection and maintenance are required at the gabions and all other engineered structures to achieve durable results.

4.1.4. *Minor, rapid mitigation measures*

A number of minor, inexpensive, mitigation measures were implemented throughout the Project implementation period. For example, on the surface of TP 5 an area of 600 m² with gamma dose rates exceeding 1.5 µSv/h, that was crossed by a footpath and grazed by cattle, was covered with inert soil material. At TP 7, 14 and 16 existing but clogged or damaged water diverting channels were repaired and partially re-built.

4.2. Relocation of TP 3 and WD 5 to TP 6

4.2.1. *Relocation of WD 5 and construction of new haul road*

The remedial action identified as most urgent was the removal of the geotechnical risk at TP 3 and the removal of the radiation risk at WD 5.

WD 5 with a volume of 65 000 m³ was then relocated to TP 6 in 2007/2008 after resettling the affected residents living on, and using the top of the dump. The waste material of WD 5 met the hydraulic and geotechnical specifications for dam construction to contain the tailings from TP 3 that were also to be relocated to TP 6.

However, before relocation of WD 5 to TP 6 could commence, a bridge across the Kara Agach River and a haul road on the right bank of the Mailuu Suu River had to be built over a length of 2252 m. Approximately 500 m of the road had to be buttressed against erosion by the Mailuu Suu River. This road was finished in 2007 and would later become part of a ring road when the tailings were moved from TP 3 to TP 6. Empty trucks would return from the disposal cell on TP 6 to TP 3, avoiding oncoming traffic along the entire haul route and especially along the narrow section upstream TP 3 where the risk of temporary blockage by landslides was highest.

4.2.2. Relocation options for TP 3

The complex internal geotechnical structure and radiation safety considerations at TP 3 required a very careful approach. In order to characterize the geotechnical, hydraulic and radioactive properties of the tailings, an extensive investigation program was implemented. Shear vane tests on a dense grid of points were a central component of this program. This program allowed the contractor to set-up a geotechnical model of the inner structure of TP 3, and confirmed earlier indications that the tailings were water saturated in large parts.

Based on the geotechnical site characterization results, in situ stabilization options for TP 3 were considered but eventually dismissed due to the perpetual need for institutional control. Eventually, relocation of TP 3 to a safer location and with a containment structure satisfying long term stability requirements was identified as the only viable option, even though relocation of TP 3 was required. A particular challenge during the optimization process was to identify the best-suited destination site. A total volume of approximately 156 000 m^3 was relocated, which included approximately 43 000 m^3 of very pulpy, saturated tailings. A guiding principle in the selection process was that no virgin land should be used for waste disposal, so that only existing waste disposal sites in and around Mailuu Suu were considered. Backfill of underground mines was also briefly discussed under the DHMP as well as by other authors [4] but dismissed as insufficient information on storage volume, geotechnical and hydraulic conditions was available.

Hydraulic transport of tailings from TP 3 to the final disposal site was considered to avoid road transport but was found to be unsuitable due to the need to add water to part of the tailings at TP 3. The excess water would have had to be managed (recycled through a return pipeline or evaporated at the destination site), and booster stations would potentially have to be built along the pipeline adding further risk and cost factors. Therefore, road transport of tailings in lockable containers was considered the only reasonable option under the local, site specific conditions. The fine-grained, partly pulpy tailings were mixed with coarser material from the existing cover of TP 3 to produce an earth-like material that could then be loaded onto, and safely transported by, dump trucks, avoiding the risk of liquefaction. Load beds of the dump trucks were covered by tarpaulins to minimize dusting.

Analysis of storage capacity, geotechnical conditions and the risk of flooding by the Mailuu Suu River and its tributaries left effectively two potential destination sites for relocated wastes: TP 15 and TP 3; see Fig. 1. TP 15 clearly has a few significant advantages over TP 3, most importantly its remote location on the high plains of the left bank of Mailuu Suu River, so that flooding risk would be completely removed. Its location would make inadvertent access and intrusion by people very unlikely. The storage volume of TP 15 would also allow relocation of further waste facilities in the future. The trough-shaped natural depression of TP 15 does not rely on human made, engineered containment structures. Understandably, TP 15 as final disposal site for TP 3 was preferred by some Kyrgyz stakeholders.

However, at closer inspection, the advantages of TP 15 were clearly outweighed by severe drawbacks. The sheer hauling distance of 15 km on a winding, very steep road would have led to very high operating costs from the outset. In addition, the access road would have to pass over extremely steep terrain, either using the existing road after costly refurbishment or building a new road at even higher cost. The winding road in a steep terrain with potential landslides would have caused traffic safety risks that are difficult to manage, especially in the event of accidental loss of radioactive cargo.

As an alternative to TP 3, TP 6 was investigated as a destination site. TP 6 is a tailings storage facility north of Mailuu Suu town, on the western (right) bank of the Mailuu Suu River. Unlike its neighbors (TP 5 and TP 7), the dam toe is high enough to be safe from erosion during extreme flood events and even after a landslide damming the Mailuu Suu River [16]. The flat surface made construction of a new containment structure relatively straightforward; material of WD 5 that had suitable geotechnical and hydraulic properties could be used. On the other hand, the haul road from TP 3 to TP 6 followed the Mailuu Suu River for a few kilometers in a section known for its landslide risk. However, road blockages and damages by landslides are considerably easier to repair at river level altitude compared to a steep hill slope. Therefore, access road from Kara Agach to the new disposal site of TP 6 had to be refurbished.

After detailed analysis of the siting options using a multi-attribute analysis and extensive discussions of the assessment results with authorities and community stakeholders (see Section 5), it was recommended by the contractor to use TP 6 as final disposal site for TP 3 and WD 5. This recommendation was adopted by the funding agency (IDA) and the Kyrgyz Beneficiary. Main drivers in this decision process were the excessive extra costs of 30% (compared to relocation to TP 6) and considerable occupational health, safety and traffic risks associated with TP 15, compared to the much lower cost and operational risk. Furthermore, the relocation of TP 3 to TP 15 could not have been completed within the time constraints imposed by IDA funding, particularly taking into account the need to substantially refurbish and maintain a haul road in very steep terrain prone to landslides. It should also be noted that the geotechnical and erosion safety of TP 6 and TP 15 were both considered satisfactory so that this aspect was **not** a differentiator between the final disposal site options. This conclusion was also shared and accepted by IDA as Contracting Authority, by the Kyrgyz authorities and by local stakeholders.

4.2.3. Relocation works of TP 3 to TP 6

Relocation works of TP 3 commenced in 2010, after successfully passing the review and permitting procedure of the engineering design and environmental impact assessment documentation by the competent authorities. It was successfully completed in summer 2013.

Pulpy tailings at TP 3 were mixed with dry cover material to provide an earth-like material that could be safely loaded and transported on ordinary dump trucks. Excess water arising during the works was pumped into a bowser and used for dust suppression at TP 6 during final disposal and compaction of tailings.

After removal of the tailings, the remaining depression ‘trough’ was complemented by a dam. The resulting pond has been used to retain the significant sediment load from the hinterland and the steep slopes. Without the sediment retention pond, the public road would need to be cleared from mud several times per year. Until now (2015), several hundreds of tonnes of sediment mud have been accumulated in the pond.

4.2.4. Side effects and additional benefits of the project

As part of the waste relocation, a road and two bridges, one of them over the Mailuu Suu River were build, which proved to facilitate access to settlements located upstream of Mailuu Suu city. The road, as it was constructed, also provides a protection against flooding to the village of Kara Agach on the western bank of the river. Both measures contribute to economic benefit of the population, improving the transport of goods from and to upstream villages, and protecting private properties in the Kara Agach case.

4.3. Radiological assessment of the works

The remedial works were carried out under best practice in radiation protection. Based on the assessment of the potential risk associated with the various remedial measures, object-specific Environmental Monitoring, Mitigation and Management Plans (EMMP) were developed by the contractor and confirmed by the DHMP project implementation unit (PIU). Main objectives of the EMMP were to keep the dispersion of radioactivity into the environment during implementation of the remedial activities, and consequently the exposure of the public, as low as reasonably achievable, and to meet the Kyrgyz regulatory standards for occupational radiation protection. Important measures to achieve these objectives included dust suppression by wetting radioactive waste surfaces, washdown of vehicles (tyres) and machinery prior to them leaving contaminated sites, enforcement of hygienic rules at workplaces, personal workers' hygiene, awareness training for workers, workplace monitoring including individual dosimetry, clearance measurements and regular inspections of the remediation sites and haulage routes.

Proper implementation of all these measures was particularly important during relocation of TP 3, not only because of the high specific activity and total activity inventory of this tailings facility, but also to address heightened awareness and concerns of public that may have turned into public opposition to this project. Therefore, the EMMP for relocation of TP 3 included a broad range of mitigation and monitoring measures that were adopted by the works contractor, a local Kyrgyz construction firm. As a result, the occupational doses could be kept lower than estimated in the Environmental Impact and Radiation Safety Assessment for the works. Occupational doses were in the range from 0.04 to 1.9 mSv per month. The higher end of this range is explained by the high specific activities of tailings material from TP 3. However, the working time during which this material was moved was around 6 months. The average of the monthly effective dose incurred by workers was 0.4 mSv per month. External radiation contributed to the workers' doses in the order of 60%, while radon/progeny inhalation and inhalation of dust–borne long lived alpha emitters were 20% each. Outside the supervised areas (including the haulage road), the measured average concentration of long lived alpha emitters in ambient air always remained below 0.4 Bq/m^3. No significant dust deposition along the haulage routes was measured.

The measurements to control occupational exposure and environmental impacts were jointly performed by the contractor and Kyrgyz laboratories and the construction contractor, which also contributed to the capacity building and know-how transfer component of the DHMP.

5. STAKEHOLDER ENGAGEMENT AND PUBLIC PERCEPTION

From the very beginning of the DHMP Component A, the contractor considered stakeholder engagement an important and integral part of the decision process and implementation of remedial measures. The project demonstrated several times the importance of working closely, and building trustful relationships, with government and community stakeholders. Important lessons related to stakeholder engagement learned or re-enforced during the DHMP included the following:

- **Accepting and explaining priorities and decisions:** Particularly under conditions of constrained financial resources and limited time for implementation it is important to explain why remediation of a certain waste facility is required, while remediation of another facility may be postponed. The arguments for the decision should be communicated in a clear, non-technical language. A driving force behind stakeholder preferences of certain, and often expensive, rehabilitation measures are the expectations of employment and economic benefits, however short term they may be;
- **Addressing fears of the public:** The contractor learned in numerous projects how difficult it may be to explain technical facts to laypersons, such as the approach to and results of a dose estimate. In Mailuu Suu, it was challenging to explain to concerned parents that uranium concentrations measured in the Mailuu Suu River do not cause health problems to their children. Another example are public concerns over the effectiveness of dust mitigation that were in reality more than sufficient to keep the public exposure during waste haulage well below all regulatory limits. Despite best efforts by international and Kyrgyz specialists, self-declared experts would often attract more attention by locals.

The contractor used various approaches to stakeholder engagement, including but not limited to the following:

- Distribution of information materials related to the project (brochures, leaflets);
- Numerous public stakeholder meetings in Mailuu Suu in order to;
  - Provide information on environmental radioactivity;
  - Communicate the results of risk assessments;
  - Present site-specific decisions and plans for remediation measures, including the prevailing constraints and the prioritization of activities;
  - Explain potential impacts of remediation activities on the environment, community health and safety, public infrastructure and traffic;
  - Address rational and irrational fears and concerns of the public.
- Regular presentations of project results to, and discussion of next steps with the competent authorities, the Bishkek/Osh based Project Implementation Unit (PIU) of the World Bank and expatriate representatives of the World Bank;
- Individual discussions with potentially affected households such as residents that would have to be resettled as part of relocation of WD5;
- Joint site investigations, sampling and measurement campaigns with local experts, aimed at building capacity in the measurement and assessment of environmental radioactivity;
- Organization of site visits by Kyrgyz technical experts and decision makers to advanced countries such as Germany (Wismut rehabilitation sites) and Austria (landslide monitoring/mitigation and riverbank protection);

— Implementation of an indoor radon investigation program, in cooperation of the local branch of the public health authorities[9], to further substantiate a fact-based dose and risk assessment;
— Implementation of workshops in Bishkek on international best practice in remediation of uranium legacy sites such as developing site-specific monitoring programs.

However, implementation of a comprehensive stakeholder consultation program does not completely immunize a project against unexpected turns of community relations. In September 2010, when haulage of tailings material was in progress, community members raised vocal concerns over suspected high radiation exposure along haul roads. People took to the streets and protested against relocation of TP 3 by blocking the haulage road towards TP 6. Relocation had to be temporarily suspended. In a public meeting in November 2010, the contractor, together with local experts and representatives of the municipal community, tried to calm down emotions and dispel irrational fears. During the meeting, attendees demanded a poll on whether relocation of TP 3 should continue or not. As a result of continuous trust building by the contractor, project supporters won a majority. Notwithstanding questions regarding the legal character of this ad hoc poll, this situation clearly demonstrated that a ‘regulatory’ license should always be supported by a ‘social’ license to carry out activities that may raise irrational fears and concerns such as those related to radioactivity. The need for continuous and situation-adapted engagement and trust building among a diverse range of stakeholders is one of the most important lessons learned during the DHMP in Mailuu Suu.

6. SUMMARY, LESSONS LEARNED AND OUTLOOK

From the authors’ experience over many years of work in Central Asia and other developing countries, a few key lessons were learned [17, 18] that can be summarized as follows:

1) In the conceptual phase, the two critical stages “site characterization” and “discussion of the justification and optimization of remedial measures and the agreement of a remedial strategy with all stakeholders” may take a long time that is usually underestimated when the project funding timeline is set-up by international donor organizations and contractors’ initial time planning;
2) Aftercare and follow-up measures should be sufficiently funded, as otherwise the success of remedial measures may be undone.

These lessons fully apply to full extent to remedial measures completed at Mailuu Suu. For site characterization the DHMP greatly was able to draw on work carried out under the TACIS project [3, 10]. However, the in-depth discussion of the justification of remedial measures and the agreement of a strategy that assigns higher priority to some objects and inevitably has to postpone work on others, could have substantially benefited from more time for all involved stakeholders to fully understand the constraints and avoid later disappointment. The contractor had to balance understandable expectations by local stakeholders that physical remediation had to commence with urgency after years of investigation and studies. This would send an important signal to people that the situation would soon improve. Apparently, due to the relatively short timeline of the project and possibly exaggerated expectations of what is achievable under severe time and budget constraints, some issues continue to surface occasionally, such as the local preference of relocating TP 3 to the remote location of TP 15.

[9] State Sanitary-Epidemiological Control or GosSanEpidNadzor.

The rational reasons for rejecting the locally preferred option and relocate the wastes to TP 6 were discussed above.

Regarding aftercare and follow-up measures, riverbank strengthening measures (e.g. at TP 2, TP 13 and others) were clearly presented to all stakeholders as temporary risk reduction measures, and designed as such. They would have been followed by a long term, sustainable solution, it should be stated that lack of follow-up funding has led to a rapid deterioration of the temporary concrete structures. The situation has been informally discussed with local stakeholders and experts at numerous occasions and requires corrective measures. The international community is well aware of the need to continue with remediation works (e.g. at tailings facilities TP2 and 13 that are most vulnerable to erosion) [19].

Stakeholder engagement from the start of the DHMP has clearly paid off. Trust building and communication with communities, training and know-how transfer to regulators and national experts have proven the right strategy to mitigate the risk of delays in the permitting and implementation phase. In this context it should also be noted that careful selection of key personnel of the contractor helped remove language barriers and ensured an intimate understanding of the host country and its political, administrative and cultural specifics.

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URANIUM MILL TAILINGS AFFECTING WATER RESOURCES IN MAILUU SUU VALLEY, KYRGYZSTAN[10]

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Abstract

Residual waste dumps and tailings from previous uranium mining activities in Mailuu Suu represent a potential risk on local water resources. In 2006, a monitoring program was initiated to determine the contamination status of local water resources in order to establish a baseline to assess the impact of coming remediation activities. Field data supplemented by laboratory experiments shed light on uranium mobilization and transport paths. The observed status of the local water resources and recommendations for necessary mitigation measures has been presented to local authorities as well as citizens.

1. INTRODUCTION

From 1946 to 1968, uranium ore was mined and processed in Mailuu Suu (Kyrgyzstan). The resulting tailings and waste rocks were deposited in nearby dumps together with below grade ore material of uneconomically low uranium content. Altogether, around 3 Mm^3 of waste materials [1] was deposited in morphologic depressions and provisionally covered.

Due to their location in a tectonically active region, the stability of rock dumps and tailings is threatened by landslides, triggered by seismic events or seasonal heavy rains. Their radioactive contents might be eroded and transferred into the river. Furthermore, landslides may block the local river Mailuu–Say and its tributaries such as Kulmin–Say, resulting in flooding of nearby dumps and tailing impoundments. This has already happened, in 1992 and 2002. Both scenarios are combined with erosion and solution processes and, thus, mobilization of the radioactive inventory. Besides affecting local water resources, mobilized radionuclides might be transported downstream beyond the Kyrgyzstan–Uzbekistan border.

Against this background, the World Bank has initiated a US $17M Disaster Hazard Mitigation Project (DHMP). In this context, the presented study was carried out in cooperation with the Kyrgyz Ministry of Emergency Situations (MOE) in order to provide a baseline to assess the contamination status of water resources. Major activities were carried out 2006 to 2009, comprising implementation of a monitoring network as well as laboratory experiments. The remediation activities of the DHMP project have been recently completed. Nevertheless, the threat from uranium mining residues is still reported to be high [2]. Therefore, the results of this study are still of actual relevance and useful for designing future remediation activities as well as assessing their impact.

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2. URANIUM MINING IN MAILUU SUU AREA

The predominating hard rocks in Mailuu Suu valley are Cretaceous and Tertiary strata, generally consisting of fine-grained sandstone and limestone sequences with intercalated marl layers. Holocene unconsolidated sediments of alluvial origin have been deposited in river valleys with a maximum thickness of up to 30 m. At outcropping Cretaceous rocks, crude oil has been observed to leak locally into the Mailuu–Say River (‘Black Water’).

Uranium mineralization is mainly developed within the limy strata of the Upper Cretaceous and — to a lesser extend — in the Lower Tertiary strata. The dominating uranium ore minerals are uraninite (UO_2), brannerite (UTi_2O_6) and its alteration products carnotite ($K_2(UO_2)_2V_2O_8 \bullet 3H_2O$) and tyuyamunnite ($Ca(UO_2)_2V_2O_8 \bullet 5–8H_2O$). The uranium content of ore-bearing rocks is reported to be relatively low with >0.5% down to 0.03%. Totally, roughly 10,000 tonnes of uranium was produced from mining activities in Mailuu Suu. The ground ore material was processed applying both acidic as well as alkaline leaching techniques. Schmidt [3] as well as local reports state that not only local uranium ores has been processed in Mailuu Suu, but also material transported from other mining districts, such as Kazakhstan or as far as from the German Ore Mountains.

Twenty–three tailing impoundments and 13 waste rock dumps have been deposited provisionally within morphologic depressions (location Fig. 1). Generally, the construction of tailing impoundments as well as dumps was carried out without the implementation of sufficient base sealing [4]. Dewatering of the tailing impoundments is commonly realized by simple drainage tubes within the gravel front at the foot of the tailing impoundments. The drained seepage water is either directed into nearby rivers or infiltrates into the subsurface. Some drainage systems were reported to be out of function due to clogging [4]. Not all waste material has been deposited superficially; some waste rock and tailing material have been redeposited in flooded mining excavations [5].

3. IMPACT OF MINING RESIDUES ON WATER RESOURCES

Hereafter, the presented findings are based on a monitoring program including 50 sampling stations (Fig. 1) in conjunction with scarce hydrogeological data about the Mailuu Suu area [6]. Sampled water types comprise seepage from tailings, river and creek waters as well as groundwater (deep and shallow aquifers) sampled from springs, dug wells, artesian wells and 11 new observation wells. The artesian wells are screened within Cretaceous or Tertiary hard rocks. Shallow wells tap groundwater from Holocene alluvial sediments. Reliable well data are restricted to the new observation wells drilled in frame of this study (M1–M11, see Fig. 1). However, even in case of an uncertain origin of a water sample due to lacking screen depth data, interpretation of major and trace constituents (hydrochemical fingerprinting) provides indications of the host material as well as specific interrelations with other water resources as described hereafter (Fig. 2).

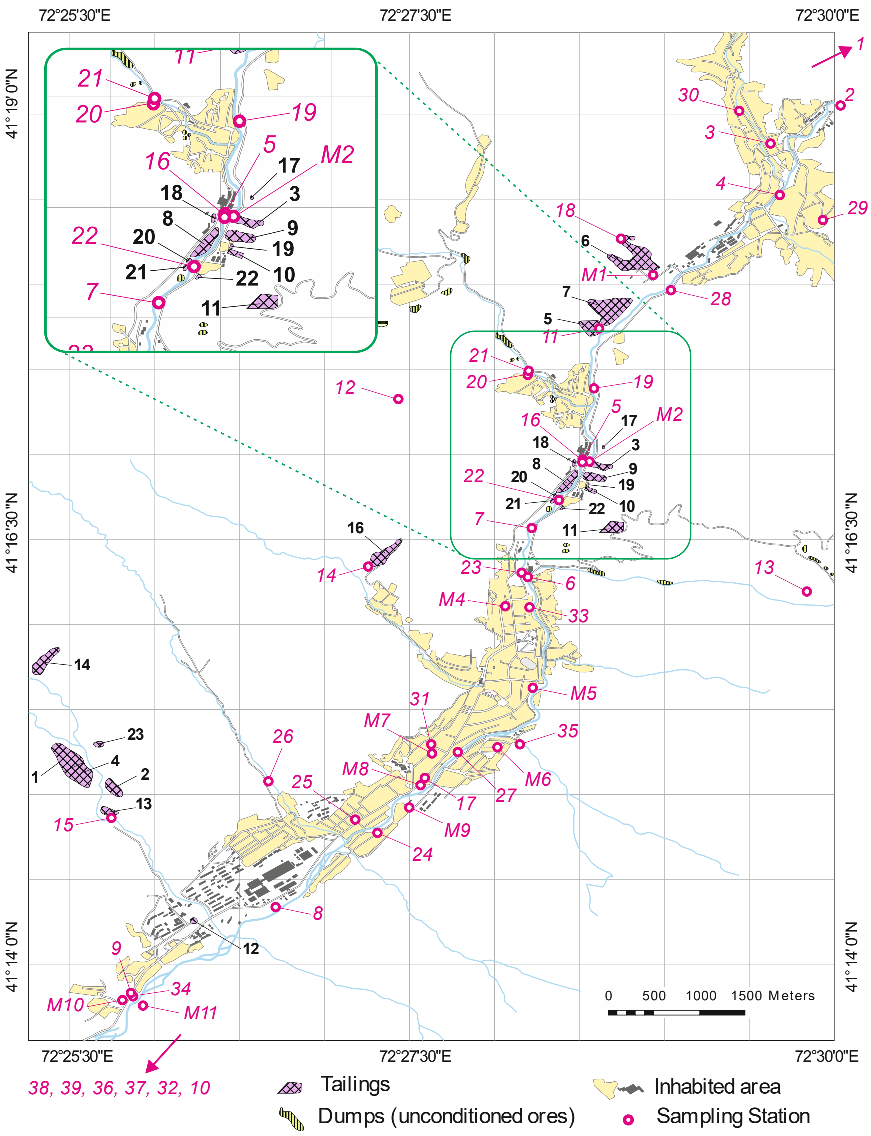

FIG. 1. Sketch map of Mailuu Suu valley with locations of dumps, tailings as well as surface and groundwater sampling stations. In frame of this study installed shallow wells are labelled 'Mx'.

The Mailuu–Say River, flowing NE to SW, represent a Ca–Mg–HCO_3 water type with low solutes and, thus, a typical meteoric composition. In contrast, the major tributary Kulmin–Say with a Na–Mg–SO_4 composition indicates a dominating impact of other sources than meteoric. In Fig. 2, river samples plot along a mixing line bordered by the northernmost Mailuu–Say water on one end and Kulmin–Say water on the other. This indicates a southward increasing impact of tributaries which drain water sources rich in sulphate and sodium.

The sampled Holocene alluvial aquifer shows a remarkable resemblance to the Mailuu–Say River water with respect to their major composition (Ca–Mg–HCO_3). Similarly to Mailuu–Say River water, shallow groundwater has a southward increasing impact of sodium and sulphate dominated fluids. Thus, the associated water composition is arranged along the mixing line discussed above (see 'GW–Holocene' in Fig. 2). This indicates a hydraulic interconnection between shallow aquifer and Mailuu–Say River. Therefore, the shallow aquifer seems to be subject to locally influx of deep groundwater and contaminated seepage water as well as tributaries, additionally to a continuous exchange with Mailuu–Say River water.

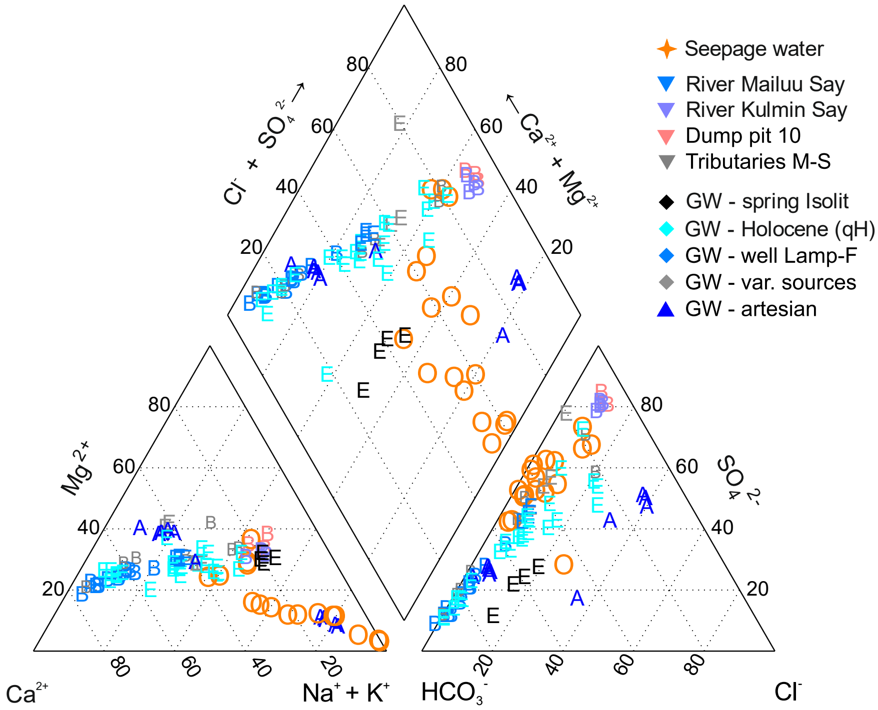

FIG. 2. Major water composition of sampled water resources (n=91), modified after [7].

In contrast to natural water resources, the term 'technogene' water is applied when influence from mining residues is likely, such as by tailings or rock dumps. The predominating water composition (Na, SO_4 and HCO_3) in this group might be explained by dissolution of sulphide and carbonate minerals, commonly present within the tailings together with a high fraction of gypsum precipitated during the leaching with sulphuric acid. Especially, the sampled seepage water leaking from tailings have a remarkably high fraction of dissolved solids (total dissolved solids (TDS) up to 10 g/L).

3.1. Uranium in natural water resources

Analyses of water samples points out that most water resources in Mailuu Suu area are at least locally affected by elevated dissolved uranium contents. From a chemotoxic point of view, uranium is the most problematic parameter. In more than 50% of all water samples, the provisional guideline value for drinking water quality recommended at the period of this study by WHO (3rd edition: 15 µg U/L) has been exceeded with maximum uranium concentrations found in seepage water up to 36 mg/L. Please note that the WHO raised the guideline value to 30 µg/L in the 4th edition published 2012, based on new data for human exposure to elevated uranium in drinking water. Further guideline values respective solutes such as sulphate (maximum 5 g/L), fluoride (maximum 10 mg/L) and arsenic (maximum 1.8 mg/L) were locally exceeded and therefore increase the risk for adverse health effects in case of consumption. Repeated monitoring revealed that contaminants' load of the observed water bodies varies seasonally mainly depending on precipitation and inflow of other water sources. The observed variability was within 30%, while being highest in case of surface waters (rivers, seepage water).

Hereafter, the sampled water types are discussed with respect to the observed dissolved uranium content (Fig. 3).

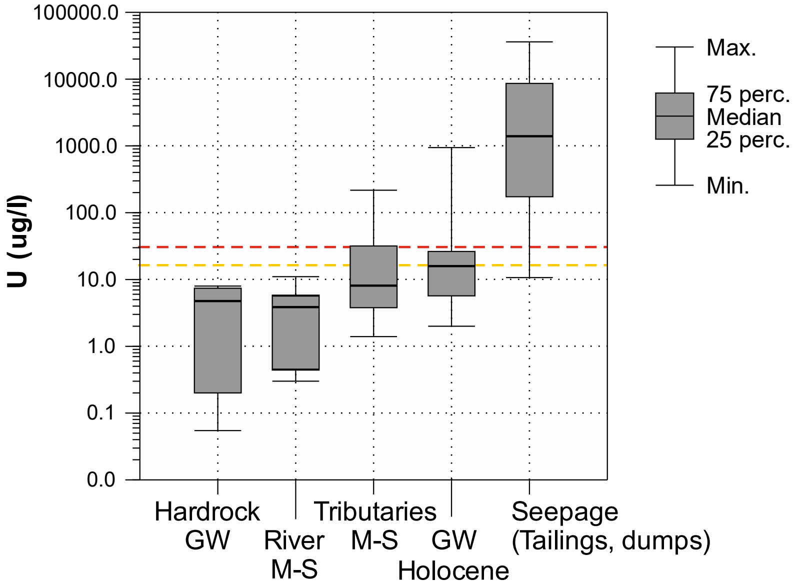

FIG. 3. Distribution of dissolved uranium in 108 water samples, grouped in terms of their origin (modified after [7]). Dashed lines indicate WHO guideline values for uranium in drinking water in red (4th edition: 30 µg/L) and yellow (3rd edition: 15 µg/L) color.

The seepage from tailings is generally dominated by high dissolved uranium (up to 36 mg/L), as a result of the tailing materials fine grain size combined with high residence time and evaporation effects (Fig. 4). Seepage discharges into receiving creeks and rivers or directly infiltrating into the subsurface.

North of Mailuu Suu valley, the main river Mailuu–Say is low in dissolved uranium (0.4 µg/L). In contrast, significant dissolved uranium has been observed in its tributaries (e.g. Kulmin–Say 170–220 µg/L). Consequently, the dissolved uranium content of the Mailuu–Say is increasing downstream but still remains below the WHO guideline for drinking water quality. The dissolved solute concentration varies in dependency of seasonal flow rate fluctuations of the Mailuu–Say and its tributaries. Consequently, the maximum uranium concentration has been observed in the south of Mailuu Suu valley at the end of the dry season in October 2006 (up to 11 µg/L, Kok–Tash area).

In Holocene alluvial sediments, lowest dissolved uranium levels have been identified north of Mailuu Suu valley (~3 µg/L). Further downstream, uranium content increases up to a maximum within the city area (30 µg/L), exceeding the current WHO guideline value for drinking water. Nevertheless, this aquifer is utilized by numerous domestic household wells. In the southernmost sampling station (Kok–Tash area) uranium has been observed to be slightly elevated but below the WHO threshold (~7 µg/L).

Artesian groundwater of Tertiary and Cretaceous aquifers can reach high uranium levels (up to 140 µg/L), probably associated with uranium ore mineralization in the host rocks. An impact of flooded mining excavations cannot be confirmed with the available data. In contrast, a deep well in the very northern area (Sarabiya) taps an unspecified, possibly Tertiary hardrock aquifer which bears very low dissolved uranium (0.05 µg/L).

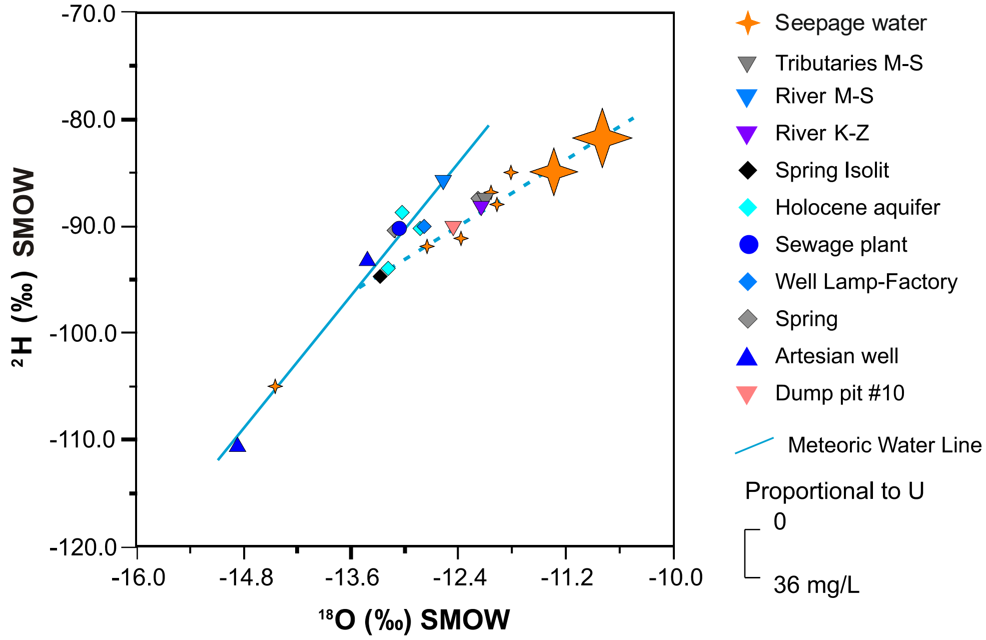

FIG. 4. Fraction of the stable water isotopes δ^2H and $\delta^{18}O$ in selected water samples (modified after [7]). Lowest values mark artesian hardrock groundwater from Sarabiya. U–rich seepage waters and receiving tributaries plot along a dashed line diverging from the local meteoric water line.

3.2. Assessment of contamination sources

Superficial mining residues such as dumps and tailing impoundments obviously represent contamination sources. However, the contamination path for specific natural water resources is quite complex since an interaction of different sources should be considered. In addition to seepage discharge from numerous dumps and tailing impoundments, artesian groundwater from Cretaceous aquifer containing dissolved uranium and metal sulphides and/or crude oil might be a significant impact when seeping into alluvial aquifers and rivers (as observed at Cretaceous outcrops north Mailuu Suu city). Moreover, uranium oxidation and dissolution in flooded mining excavations might enhance dissolved uranium levels.

Another perspective to the specific relevance of contamination sources for superficial water resources in Mailuu Suu area is provided by analysis of stable hydrogen and oxygen isotope data (Fig. 4). While the natural water samples generally plot along the local meteoric water line, high uranium seepage waters as well as the sampled tributaries (including Kulmin–Say) are characterized by an increased $\delta^{18}O$ fraction. This hints to evaporation effects, which take place in poorly capped tailings and dumps and resulting in accumulation of heavy oxygen isotopes as well as non-volatile solutes ($r(\delta^{18}O, TDS) = 0.62$). Based on the available stable isotope data, the water composition of sampled tributaries including Kulmin–Say is dominated by uranium rich seepage water from dumps and tailings. This should be confirmed in future monitoring campaigns including stable isotope analysis.

Radiochemical leaching experiments with local tailing material (Tailing 3) as well as thermodynamic calculations have been carried out to get insight into the uranium mobilization process within the tailing impoundments [8]. In summary, formation of dissolved uranium is generally controlled by pH/Eh conditions as well as the availability of the ligands bicarbonate and calcium [8, 9]. The dominating U species are calcium uranyl carbonates ($Ca_2UO_2(CO_3)_3$ and $CaUO_2(CO_3)_3^{2-}$). These are mobile species in sediments with neutral or negatively charged mineral surfaces. Moreover, a significant proportion of uranium has been mobilized as uraninite colloids (<200 nm) with 20 ± 5% of total mobilized uranium.

Vandenhove et al. [10] identified Tailing 3 as the dominating environmental hazard with a total radiation inventory of 650 TBq, as much as 60% of the total radiation of all tailings impoundments. Consequently, recent remediation activities relocated Tailing 3 to a safe disposal site. However, considering the water transport path other sources are found to be more relevant as shown in Table 1. Based on our field observations, in 2006 seepage from Tailing 5 represented a major contaminant for Mailuu–Say River with a calculated load of 122 g uranium per day. Notably, the relocation of Tailing 3 has limited impact on improving water quality due to the comparatively low daily uranium discharge into the Mailuu–Say.

TABLE 1. APPROXIMATE URANIUM RELEASE OF SELECTED SOURCES DISCHARGING INTO THE MAILUU–SAY RIVER, CALCULATED FROM OBSERVATIONS DURING FIELD CAMPAIGN IN 10/2006 (MODIFIED AFTER [7])

Source	U [mg/L]	Discharge [L/min]	U release [g/d]
Seepage Tailing 3	1.8	0,5	1
Seepage Tailing 5	8.5	10	122
Seepage Tailing 16	36	0.1	5
Kara Agach River	0.04	500	28
Kulmin–Say River	0.17	100	25

4. RECOMMENDED MITIGATION MEASURES

A local water supply facility was designed under Soviet governance with the aim to provide drinking water for 20 000 people and, therefore, never achieved service to all residents of Mailuu Suu. The supply facility providing uncontaminated river water upstream the mining area degraded during the last decades. Consequently, an increasing number of households directly utilize local water resources from deep artesian wells, simple dug wells and local rivers. Responsible authorities are strongly recommended to modernize and enhance the central water supply.

Furthermore, seepage water catchment and disposal systems need to be designed to reduce environmental impact of identified contamination sources. The quality of water resources should be observed by continuous monitoring approach distinguishing between surveillance, operational and investigative monitoring. This can only be realized by a long term allocation of funds and expertise as well as sufficient laboratory capacities. Finally, all mitigation measures need to be combined with systematic information campaigns in order to improve awareness and to reduce risks of the affected local population.

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EXTRACTION OF URANIUM FROM MONAZITE ORE IN THAILAND[11]

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Abstract

Monazite ore in Thailand is found in association with tin deposits which are mainly mined in the southern peninsular of Thailand. Traditional ore dressing techniques are used to separate monazite from the trailing of tin ore. Domestic monazite is a phosphate ore composing mainly of combined rare earth oxides in the range of 50–60%. Uranium composition in monazite is about 0.3–0.8%. Monazite also contains thorium in between 5 and 10%. The breakdown of monazite ore has been studied and carried out using alkali process. Monazite sand was wet ground to -325 mesh size and digested with hot concentrated caustic soda at 150°C for 3 hours. Most of the phosphate compounds then turned into hydrous metal oxide and were filtered and washed to remove the remains of alkali solution. The hydrous metal oxide cake was dissolved into chloride solution using hydrochloric acid and the solution was filtered to remove undigested monazite and gangue. Uranium and thorium were selectively precipitated from the chloride solution by adding sodium hydroxide solution to raise the pH of the chloride solution to 4.5. The uranium and thorium hydroxide filtered from the chloride solution was dissolved into nitrate solution using nitric acid. Uranium was then separated from the thorium by solvent extraction using solvent of 5% tributyl phosphate (TBP) in kerosene. The uranium obtained from the first extraction step still contains some thorium and traces of rare earth elements and requires further purification to obtain high purity of uranium product. The thorium remained in the raffinate can be extracted with 40% TBP in kerosene.

1. INTRODUCTION

Uranium exploration in Thailand has been carried out since the early 1970s by the Department of Mineral Resources. Uranium occurrences were found in various geological environments including sandstone and granite host rocks. Sandstone type mineralization occurs in Phu Wiang district of Khon Kaen province in north–eastern Thailand. Uranium occurrences in granite associated with fluorite have also been discovered in Doi Tao district, Chiang Mai province and Muang district of Tak province in northern Thailand. However, these uranium deposits were reported to be small and required further exploration.

In the southern peninsular of Thailand, uranium bearing minerals, namely monazite and xenotime, were found in association with tin deposits which were mainly mined in Phuket and Phang Nga provinces (Fig. 1). Traditional ore dressing techniques can be used to separate monazite, xenotime and other heavy minerals from the trailing of tin ore. Monazite mainly consists of phosphate compounds of rare earth elements such as Ce, La, Nd, Sm, Pr and Gd. A few per cent of the elements Th and U are also present in the ore, which raised the interest of then the Chemistry Division, Office of Atomic Energy for Peace to start a research project for separation of U and Th from monazite ore in 1975. The project has been developed to the establishment of Rare Earth Research and Development Center (RRDC) which is located in Prathumthani. RRDC operated a semi-pilot scale plant for the monazite ore breakdown process with the separation of U, Th and rare earths from the ore.

[11] Presented at the Technical Meeting on Optimization of In Situ Leaching (ISL) Uranium Mining Technology, Vienna, Austria, 15-18 April 2013.

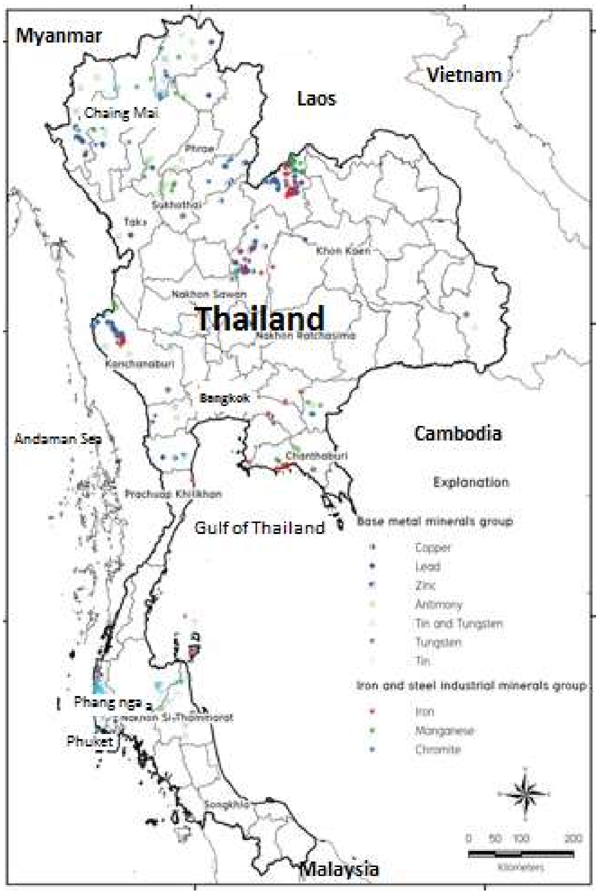

FIG. 1. Monazite found in association with tin deposits in the south of Thailand (reproduced from Ref. [1] with permission).

2. MONAZITE ORE BREAKDOWN PROCESS

Monazite ore is a phosphate rock of rare earths and also including thorium and uranium. This ore can be chemically decomposed by using strong acid or strong base, i.e. by acid or alkali processes respectively.

In acid process, H_2SO_4 is used to break down the ore in a digester at temperature about 200ºC and the occurring reactions are:

$$2\ RE(PO_4) + 3\ H_2SO_4 \rightarrow RE_2(SO_4)_3 + 2\ H_3PO_4$$

$$Th_3(PO_4)_4 + 6\ H_2SO_4 \rightarrow 3\ Th(SO_4)_2 + 4\ H_3PO_4$$

where RE stands for mixed rare earth elements. The sulphate products are dissolved in water and Th or U can be separated from mixed rare earths by selective precipitation. This acid process yields phosphoric acid (H_3PO_4) as by-product.

In alkali process, NaOH is used to digest the ore at temperature about 140ºC as follows:

$$2\ RE(PO_4) + 6\ NaOH \rightarrow 2\ RE(OH)_3 + 2\ Na_3PO_4$$

$$Th_3(PO_4)4 + 12\ NaOH \rightarrow 3\ Th(OH)_4 + 4\ Na_3PO_4$$

The hydroxide products are filtered from the phosphate solution and dissolved in acid for further separation of each element. Trisodium phosphate (Na_3PO_4) is the by-product from this alkali process.

The typical composition of domestic monazite ore analyzed by the Chemistry Division, Office of Atomic Energy for Peace, Thailand is shown in Table 1.

TABLE 1. COMPOSITION OF DOMESTIC MONAZITE ORE OF THAILAND

Composition	%
Thorium oxide (ThO_2)	4.5 – 10.6
Uranium oxide (U_3O_8)	0.24 – 0.79
Total rare earth oxide	47 – 58
- Cerium oxide (CeO_2)	19 – 23
- Lanthanum oxide (La_2O_3)	7 – 15
- Neodymium oxide (Nd_2O_3)	6 – 11
- Praseodymium oxide (Pr_6O_{11})	1.6 – 3.4
- Samarium oxide (Sm_2O_3)	0.7 – 1.6
- Gadolinium oxide (Gd_2O_3)	1.0 – 1.4
- Dysprosium oxide (Dy_2O_3)	0.4 – 1.9

At RRDC, alkali process has been used to decompose monazite as shown by diagram in Fig. 2. Monazite ore with particle size of 1–3 mm, similar to beach sand, needs to be ground to pass a 325–mesh sieve before feeding into the digester. A ball mill with wet grinding process is used. The ore is reacted with 50% NaOH at 140ºC for 3 hours using the ore:NaOH ratio of 1:2 in a stainless steel digester with heating jacket. The viscous digestion slurry is diluted with water and filtered to separate the digestion cake from Na_3PO_4 solution. The Na_3PO_4 by-product in the solution is recovered by evaporating the solution for the crystallization of Na_3PO_4 crystal. The residual mother liquor after separation of Na_3PO_4 contains high concentration of NaOH can be recycled to the digestion stage.

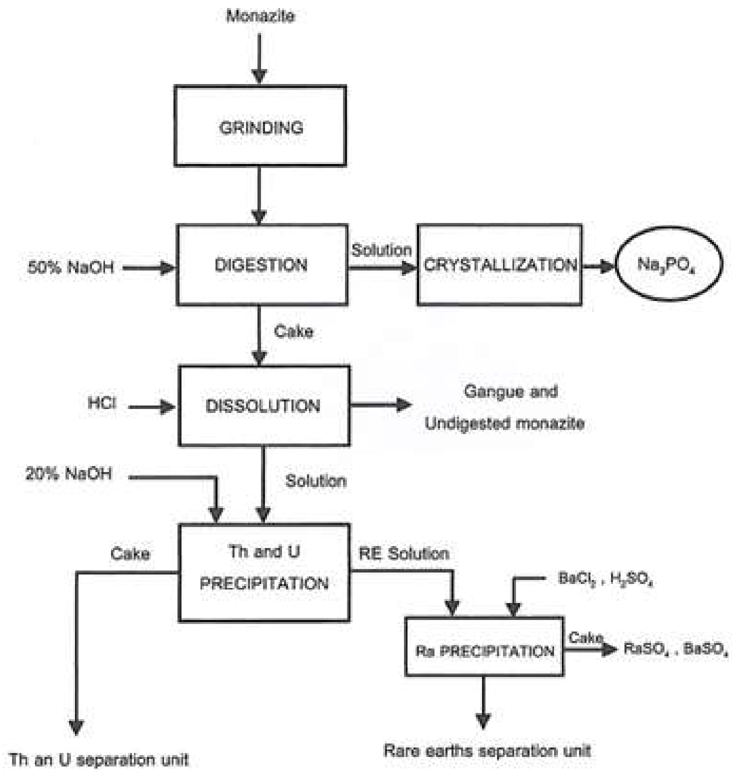

FIG. 2. Monazite ore breakdown by alkali process.

The hydroxide cake of Th, U and mixed rare earths is dissolved with HCl and filtered to separate undigested ore and gangue from the chloride solution. The separation of Th and U is accomplished with an initial precipitation by adding 20% NaOH into the chloride solution to raise its pH to 4.5. Th and U chlorides are all together turned to hydroxides and filtered out as Th–U cake. The filtrate contains rare earth elements before feeding to rare earth separation unit needs to be decontaminated because it also contains a trace of radioactive elements which are the decay products of U and Th. The decontamination can be carried out by removing of Ra which is an essential product from the decay series. As very small amount of Ra is present in the chloride solution, co-precipitation technique is used to remove Ra by adding $BaCl_2$ into the solution and precipitating with H_2SO_4.

3. SEPARATION OF TH AND U

Th and U in the Th–U cake from the ore breakdown process can be separated by solvent extraction technique as the process diagram shown in Fig. 3. Feed for the solvent extraction is prepared by dissolving Th–U cake with HNO_3 and adjusting its concentration to 40–50 gm/L and 4 N free acid. Organic solvent used for the extraction of U is 5% tributyl phosphate (TBP) in kerosene. The extraction is carried out in a set of pulse perforated plate column as shown in Fig. 4. The column made of glass tube containing stainless steel or Teflon perforated plates located vertically at regular intervals inside the column. Air pulsing mechanism is used to create oscillating motion of both liquid phases along the column height. Feed and solvent are introduced to the column in a continuous counter-current flow where the heavier aqueous phase of feed enters at the top and the lighter organic phase of solvent enters at the bottom of the column.

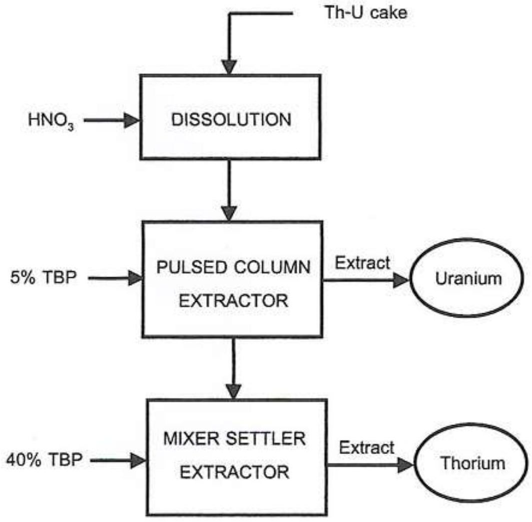

FIG. 3. Monazite ore breakdown by alkali process.

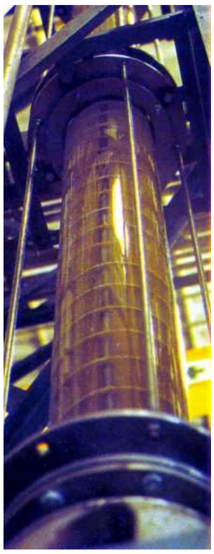

FIG. 4. Pulse perforated plate column.

The extraction is divided into 3 steps namely extraction, scrubbing and stripping as shown in Fig. 5. Since Th–U cake may contain some rare earths that precipitate along with Th and U during the initial precipitation, these rare earths are also dissolved into the feed. In the extraction step, most of U is extracted into the solvent phase. However, a small amount of Th and rare earths can also be extracted into the solvent. Thus, it requires to wash these elements from the extract or U–loaded solvent in the scrubbing step where 2 N HNO_3 is used as the scrubbing solution. Then, water is used to backwash all U from the solvent in the stripping step resulting in the product of U solution which can be precipitated for further re-extraction process to obtain high purity of uranium product.

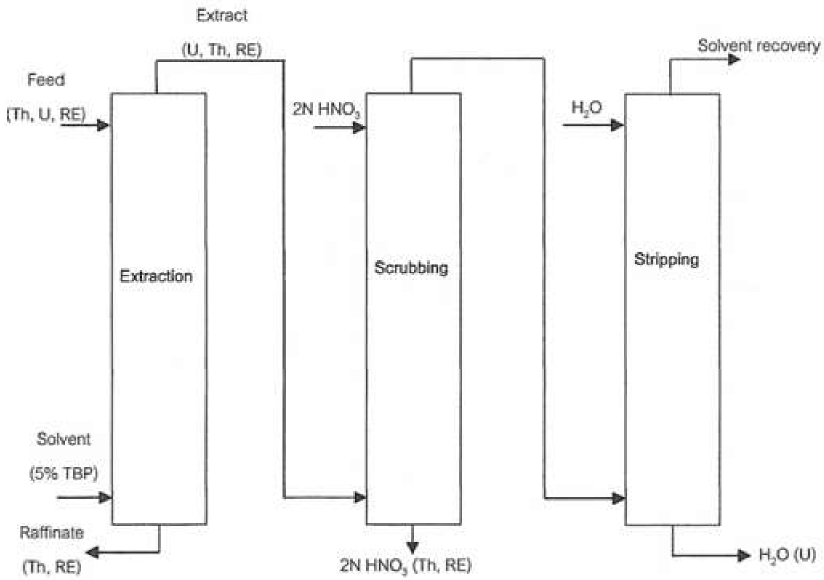

FIG. 5. Solvent extraction of uranium.

The raffinate from the uranium extraction unit is fed to the thorium extraction unit which is also divided into 3 steps similar to the uranium extraction unit. In this unit, 40% TBP in kerosene is used as the extraction solvent. 2 N HNO_3 and water are also used in the scrubbing and stripping steps, respectively. Dissimilar to the uranium extraction unit, the extraction equipment used for Th extraction is a set of pump mix mixer-settlers (Fig. 6) which are horizontally mounted extractors in contrast to the vertical column. These mixer-settlers are also operated in a counter-current flow pattern. A mixer-settler extractor is normally composed of multiple extraction stages where each stage consists of two vessel chambers called mixer and settler. In mixer, the liquid phases are mixed together by agitation and the mixed liquid phases are brought into settler for the liquid phases to separate out again. Each phase then flows to the adjacent mixer in the opposite direction. Each mixing chamber contains a small centrifugal pump or impeller in the form of a hollow shaft fitted with a disc having a designed hole in the center. Rotation of this impeller immersed in a liquid sucks the liquid up the shaft and ejects it through the hole, thus causing mixing in the vicinity.

Some of the raffinate after extraction of U and Th can be recycled for the dissolution of Th–U cake. Similarly, both 5% TBP and 40% TBP solvents can be reused after reconditioning and saturated with HNO_3.

FIG. 6. Pump mix mixer-settlers.

4. WASTEWATER TREATMENT

Wastewater from the monazite ore breakdown process is mainly the filtrate from the precipitation of Th, U and rare earths. As NaOH is used mostly for the precipitation of Th, U and rare earths in the chloride and nitrate solution, the wastewater then contains either NaCl or $NaNO_3$ with its pH about 10–12. However, filtrate from the precipitation of U or Th will be checked for its radioactivity before releasing to the treatment plant. If the activity is high, the filtrate will be kept in the temporary storage tanks until its activity decreases to a safety limit. Wastewater from the process is collected in the sump as shown in Fig. 7 where there are three sumps for separated processing units. When the sump is full, wastewater is pumped to the neutralization tank where HCl or NaOH is used to adjust its pH to 7. After neutralization, the effluent is led to one of the six evaporation ponds and stored until all the water is naturally evaporated. The remaining residue of salt compounds in the evaporation ponds will be collected and kept in a storage building.

During wastewater neutralization, if there is precipitate, the effluent will be directed to sedimentation tank where precipitate is separated by means of drying bed or pressure filter. Waste treatment system also contains an emergency pond to receive overflow water from evaporation ponds and filtrate from the sedimentation tank. It is noted that all the wastewater is kept in the plant and is not let out to the environment. Wastewater in the evaporation ponds is monitored regularly for radioactivity and Th, U content. The reported results are mostly in the standard limit of the wastewater quality. Aeration in the evaporation ponds is sometimes needed to prevent the wastewater in the pond from stinking.

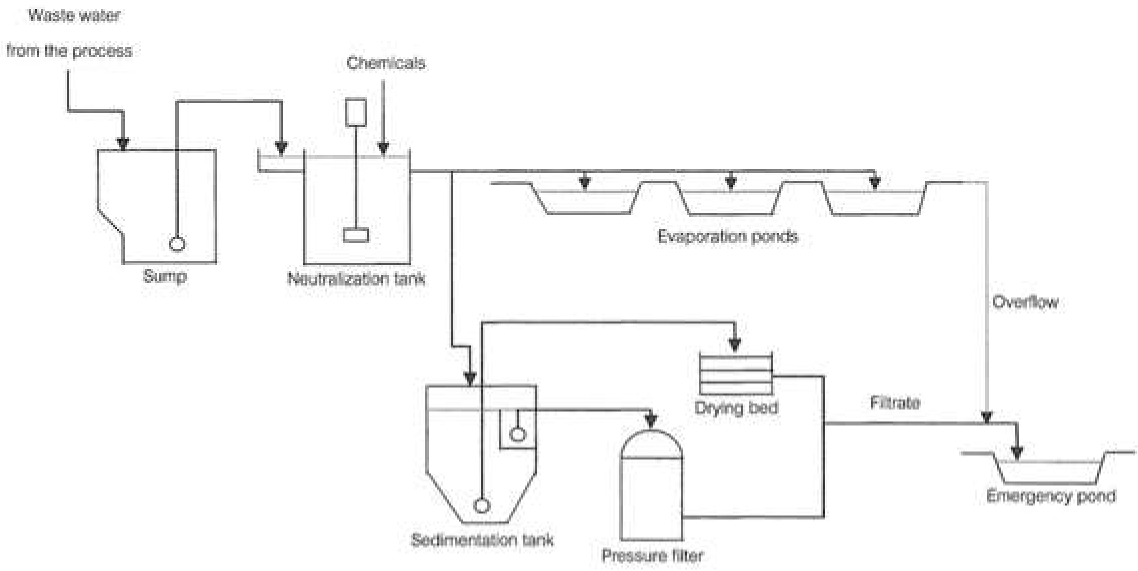

FIG. 7. Wastewater treatment plant.

5. CONCLUSION

Uranium contained in monazite as the phosphate compound was successfully extracted at then Office of Atomic Energy for Peace (the name of the office was changed to Office of Atom for Peace in 2002). The existing process employed NaOH to break down the phosphate compound and convert to hydroxide which later was dissolved by HCl. Uranium in chloride solution together with thorium was selectively precipitaed at pH 4.5. Then uranium and thorium precipitate was dissolved in HNO_3 and solvent extraction process with TBP/kerosene was used to separate uranium from thorium. The uranium extracted from the primary extraction required further purification by solvent extraction to obtain high purity product.

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REACTIVE TRANSPORT SIMULATION OF URANIUM ISL AT THE BLOCK SCALE: A TOOL FOR TESTING DESIGNS AND OPERATION SCENARIOS[12]

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Abstract

This study details the development of a 3–D reactive transport modelling approach dedicated to simulate acid ISL production of uranium. The model relies on an appropriate description of uranium bearing aquifer: 3–D geological model, based on geostatistical simulation of uranium grade and hydrodynamic parameters. Also, a correct assessment of the chemical reactions at stake is necessary. The ISL operations are then simulated using the versatile reactive transport code HYTEC. Among other simulation results available, the evolution of the uranium concentration at production wells can be predicted. The model was applied at the technological block scale (50 technical wells) on the KATCO mine in Kazakhstan. The simulation reproduces the behaviour in terms of uranium recovery and acid consumption. It also helps quantitatively understanding the behaviour of the exploitation, and identifying weak spots of the leaching process. Finally, it is possible to use the simulation to optimize the production (increased uranium yield or reduced reagent consumption) by comparing the results under several production scenarios (injection rates, fluid composition and well field geometry).

1. INTRODUCTION

Numerous applications in the broad field of geoscience involve water circulation in porous media, and associated chemical reactions: influx of disequilibrated waters modifies the local chemistry (mineral dissolution or precipitation, surface reactions), which in turn can modify the pore structure and the hydrodynamics. Reactive transport provides an effective way to investigate such complex systems. This approach is based on processes [1]. The numerical simulations solve the hydrodynamics equations (flow, solute transport, heat transfer), using parameters such as permeability, porosity and prescribed boundary conditions. On the other hand, the codes can handle a large number of chemical or biochemical reactions, both under equilibrium or kinetically controlled; the resolution is constrained by extensive thermodynamic databases, kinetic constants provided by laboratory measurements or literature. All these processes are solved in a coupled way.

This approach has been developed for the last thirty years [2] with a strong driver from research on nuclear waste disposal. The field of applications has broadened over the years, and includes near- and far-field processes for radioactive waste disposal [3, 4] geological storage of CO_2 or acid gases [5, 6] and the degradation of geomaterial (concrete, cement, glass, particularly in a geological environment) [7, 8].

ISL is an effective mining technique for uranium exploitation. It involves the injection, under fast flowrates, of leaching solutions through injection wells. Within the deposit, uranium is dissolved, among other reactions. The dissolved uranium is recover through production well,

[12] Presented at the Technical Meeting on Optimization of In Situ Leaching (ISL) Uranium Mining Technology, Vienna, Austria, 15–18 April 2013 (updated 2015).

and finally retrieved from the solution using ion exchange resins in a process plant. The solution is then recycled to the well field. The management of the operation is largely based on empirical expertise. However, the processes at stake within the deposit are typically those taken into account in reactive transport codes. This approach thus offers interesting new insights for the qualitative and quantitative understanding of the behaviour of the exploitation. Since the approach is based on processes, it has a potential for a priori prediction of the local production (cell or block size), or alternatively for the investigation of the yield under different exploitation scenarios; finally, the simulations can be extended to include the long term impact of the exploitation.

AREVA leads an ISL operation in Kazakhstan, through its joint venture KATCO. The Moynkum deposit is located in the Chu–Sarysu basin [9]. The roll-front formation is 400 m deep, within a loose sand aquifer. The R&D (Research and Development) Department at AREVA Mines supports a multi-annual program on in situ recovery (ISR) optimization. One of the actions undertaken is the use of reactive transport codes, with a view to qualify the approach, test their prediction capacity and its application for devising and discriminating between several alternative production scenarios. This research program has been conducted for the last 7 years at AREVA Mines, in association with the Geosciences Department at MINES ParisTech, where the reactive transport code HYTEC is developed [10].

This paper presents the reactive transport approach, as it is developed at AREVA Mines. The workflow is presented. It relies on an accurate description of the geology, geochemical environment, so that the processes described by the code are precisely constrained. An example is provided, based on a production block in the KATCO mine. The code provides a correct representation of the fluxes, including uranium recovery and acid consumption.

2. MATERIALS AND METHODS

2.1. Reactive transport code HYTEC

HYTEC is a numerical code for the resolution of reactive transport systems. It couples hydrodynamic flow and multicomponent transport with biogeochemical processes [10, 11]. In its current version, HYTEC deals with stationary and transient flow and transport in saturated, unsaturated or two-phase conditions. Heat transport is accounted for and coupled with flow (heat advection, feedback on water viscosity). HYTEC is massively parallelized, and can be run on large multiprocessor computers.

HYTEC is developed within the framework of the Reactive Transport Consortium, a research group, which includes industrial (for the 2014–2016 program, AREVA, Bel V, EDF, Lafarge) and semi-public partners (CEA, IRSN). This structure not only allows the development of HYTEC on a long term basis, it also triggers a wide variety of application domains, from small scale material science (e.g. corrosion of steal, waste or glass dissolution, degradation of cement) to large scale geological problems (e.g. geological storage of CO_2, radioactive waste disposal). HYTEC therefore aims to be a configurable and operational tool, applicable to any reactive transport problem.

HYTEC chemical module is based on CHESS, a versatile geochemical speciation code. It allows for the simulation of aqueous speciation, precipitation and dissolution of solid (mineral) phases, interface reactions (based on a choice of surface complexation and ion exchange models), temperature dependencies and radioactive decay with multi-ancestor and multi-descendant filiation, to cite a few of the possibilities. The model is unlimited with respect to the number of species taken into account. The species and reactions are defined by extensive thermodynamic databases. All reactions can be modelled using the local equilibrium assumption, full kinetic control or a mixture of both. Microbial reactions are accounted for by specific kinetic reaction laws.

For this study, the thermodynamic database EQ3/6 was used [12].

2.2. Data set

The reactive transport HYTEC needs as many field parameters as possible. Unknown parameters can be supplemented by a fitting approach. However, parameter adjustment is performed using a posteriori production data, so that it decreases the predictive capacity of the code. Several types of data are required:

1) An accurate description of the geology and particularly the spatial heterogeneity (lithofacies, mineralogy, uranium grade);
2) A geochemical model (main chemical reactions, and their kinetics);
3) The well field geometry;
4) An exploitation scenario (flowrates, fluid composition).

2.2.1. Geological model

Due to the circulation of uranium bearing oxidized fluids through a highly permeable aquifer, the genesis of the orebody, controlled by the permeability and the redox properties of the host rock, results in complex geometries associated with strong uranium grades heterogeneities [9]. On completion of geological field data (core description, radioactivity gamma and resistivity logs from exploration drilling), 3–D modelling of the deposit was performed using a pluri-gaussian simulation method. These stochastic simulations lead to the construction of several realizations of 3–D discretized geological block models describing the variability of lithology, redox facies and uranium grade [13].

Simulations were run on a 5 m × 5 m × 1 m rectilinear grid leading to 350 000 cells for the application presented in this paper. The same grid support was used for the HYTEC simulations.

2.2.2. Geochemical model

Mineralogical analyses of the deposit (mineral type and concentration) are available, for the mineralized (reduced) and barren (reduced or oxidized) facies. Along with the analysis of the injection fluid (sulphuric acid and accumulating recycled dissolved elements), a very large set of aqueous speciation and fluid-rock reactions are possible, which can be very CPU demanding for (very large) reactive transport simulations.

A geochemical model was set up to represent the sulphuric acid/rock interaction. Starting from an exhaustive chemical description of the system, the reactions were first hierarchized, then simplified to limit the CPU (and memory) intensity of the code. The controlling reactions are the oxidative dissolution of U(IV) bearing mineral, the acidic dissolution of carbonates and clays. pH is controlled by the injecting solution, and interaction with mineral buffers. Likewise, Fe^{3+} is the main oxidizer in the system; its concentration is controlled by the solubility of iron oxi-hydroxides (dependent on pH), dissolution of iron bearing minerals in the deposit, and oxidation of reduced elements (including U(IV)).

Based on the chemical analyses and the simplified chemistry hypotheses, a mineralogical model of the system was proposed: Table 1. The kinetic parameters of precipitation/dissolution are taken from the literature [14], modified with regard to laboratory experiments [15, 16]. Finally, some kinetics data (or reactive surface areas) were adjusted using production data from previously studied areas in the mine.

The injection fluid is recycled from the processing plant, after uranium retrieval. The fluid is thus an average from waters collected over different part of the mine. As result, the composition out of the plant is relatively stable in time. The pH (or equivalently sulphuric acid content) is adjusted before injection, according to the acidification scenario.

TABLE 1. MINERALOGICAL MODEL FOR THE MAIN GEOCHEMICAL UNITS OF THE DEPOSIT

Minerals	Oxidized (barren)	Reduced (barren)	Reduced (mineralized)
U(IV) bearing phase	0	0	Simulated grade
Carbonate	+	+	+
Iron oxy–hydroxide	+	0	0
Cristobalite*	+	+	+
Smectite*	+	+	+
Kaolinite*	+	+	+

* indicates kinetically controlled minerals

2.2.3. Well field geometry

The geometry of the well field is explicitly defined: the position of the screens is described in the 3–D grid, for each injection and production well (c.f. Fig. 1). The well position is superimposed on the facies (permeability, mineral composition, uranium grade) derived from the geological block model.

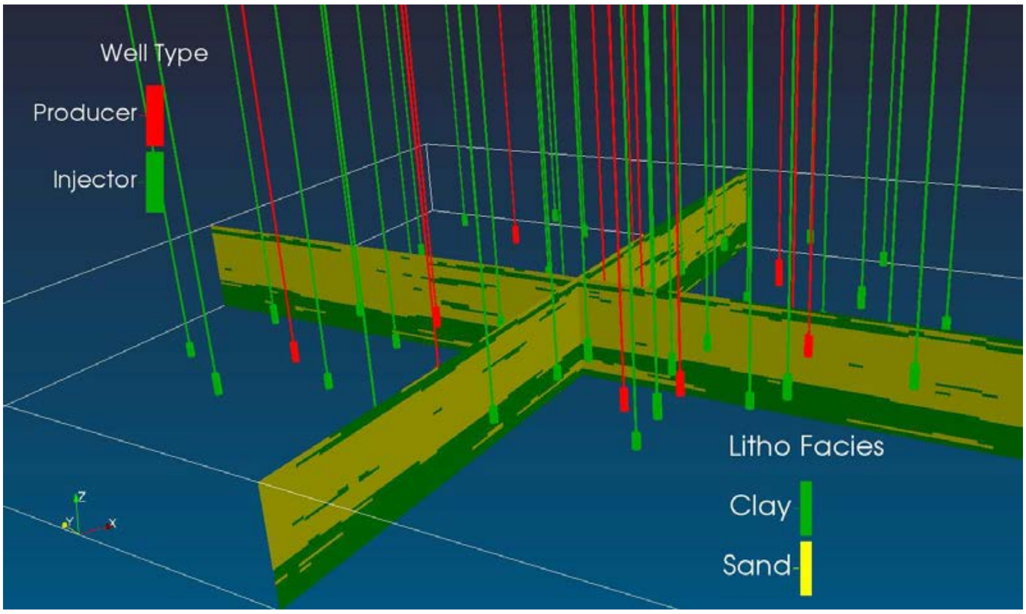

FIG. 1. Well position (producers in red, injectors in green) for the technological block used in this paper application, over two cross-sections of the geological block model.

2.2.4. Exploitation scenario

Apart from the well field geometry, the exploitation is piloted only through well flow rates (for all wells) and injection fluid composition.

For the simulation, a prescribed flow rate is imposed on each well. This flow rate can be modified over time (without limitations), and is used (globally) to constrain the transient saturated flow in the system. Likewise, the fluid composition (mostly acid content) is prescribed in the simulation; its evolution can be controlled at any desired time step.

These options allow the simulation of any exploitation scenario: for instance, a heavy acidification at the beginning of the block life followed by weaker acid addition over time, or a change of the well flow rates to increase the yield locally in the block. Alternatively, the history of a block can be simulated, with a view to qualify the model or adjust the parameters. In this case, the modification of the flow rates can reproduce well defects, well closure and even new wells drilled during the exploitation.

3. SIMULATION RESULTS

3.1. Hydrodynamic behaviour

A first output of the model is the hydrodynamic behaviour of the block. The velocity field is calculated on each node of the grid for each time step. On Fig. 2, the result is presented as streamlines. The fluid migrates from the injectors to the producers; the velocity field depends on the local prescribed flow rates and the permeability of the deposit. As a rule, direct lines between wells are faster than longer streamlines; particularly, some streamlines visit areas out of the cells (and the block), and have the slowest velocities.

Even without taking the chemistry into account, this representation gives a broad idea of the efficiency of the leaching. Areas with poor acidification (e.g. due to clay barriers) can be identified. Also, the simulation can help match the high local flow rate with high grade areas.

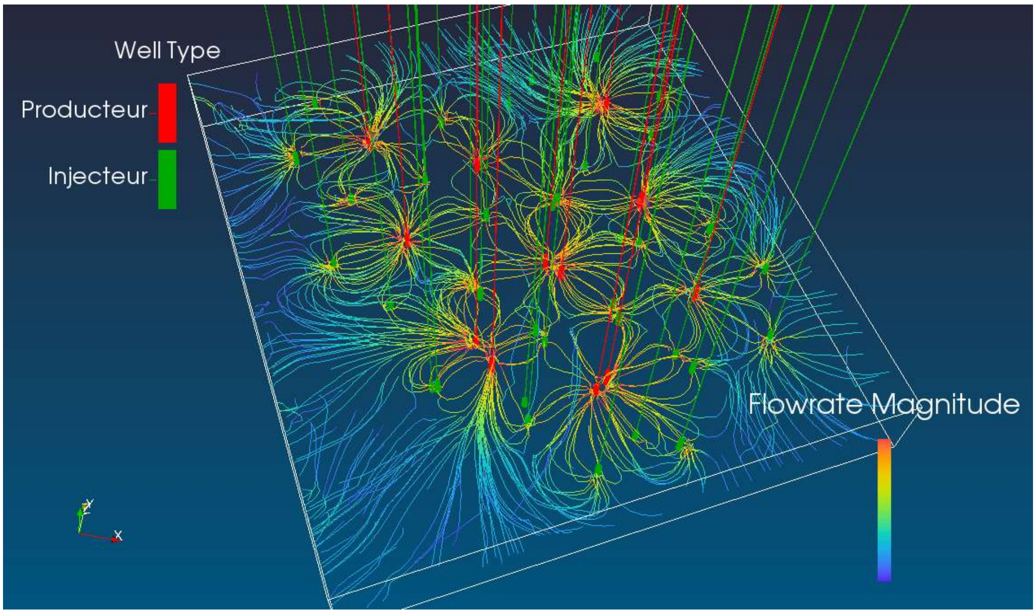

FIG. 2. Streamlines representation of the velocity field in a reactive transport simulation of a block in the KATCO exploitation.

3.2. Acidification of the deposit and uranium dissolution

Fluid injection leads to the progressive acidification of the ore body: Figure 3 shows the early stage of acidification. The visualization of the HYTEC results is performed with the software ParaView [17] here with a filter for zones under pH 3 only. The progression of the pH front is slowed down, due to the presence of fast mineral buffers (carbonates). After 40 days, the carbonates are mostly dissolved in the whole block; on the long time, the pH is controlled by the competition between the acidic influx and the kinetics of slower buffers (clays).

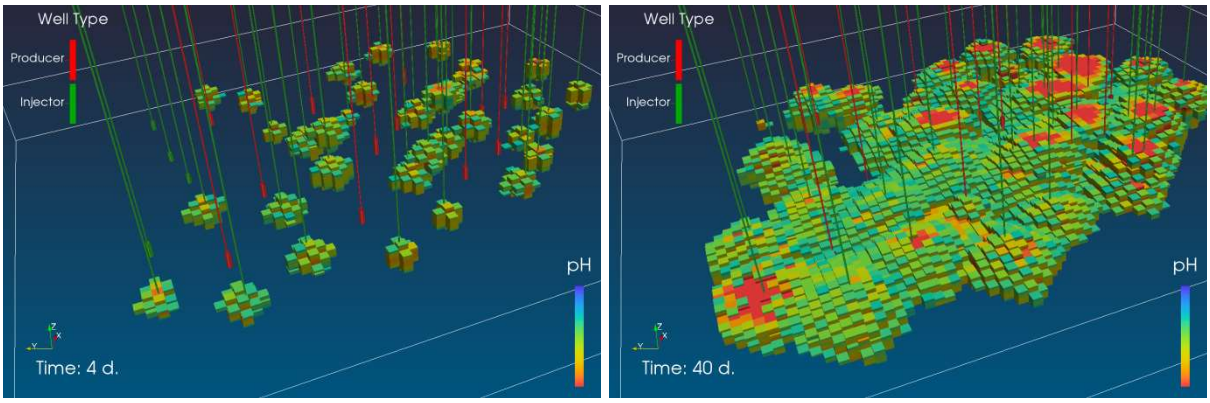

FIG. 3. Reactive transport simulation of the early stage of acidification of a block: pH<3 at 4 days (left), 40 days (right).

pH under 2.5 allows for the transport of dissolved Fe(III), and its local dissolution when iron bearing minerals are available. This in turn allows for the oxidative dissolution of uranium: (cf. Fig. 4). The spatial variability in U(IV) bearing mineral distribution generates a heavy heterogeneity in the dissolved uranium profiles. Uranium transport and the mixing in the convergence zones around production wells will constrain the concentration at each producer. Fast streamlines through high grade areas would yield high concentration fluids; however, they will be diluted by slower streamlines, or fluid migration from barren (or lower grade) areas. The concentration profiles evolve continuously, as uranium is exhausted locally, and other mineral buffers change the pH or Fe(III) content.

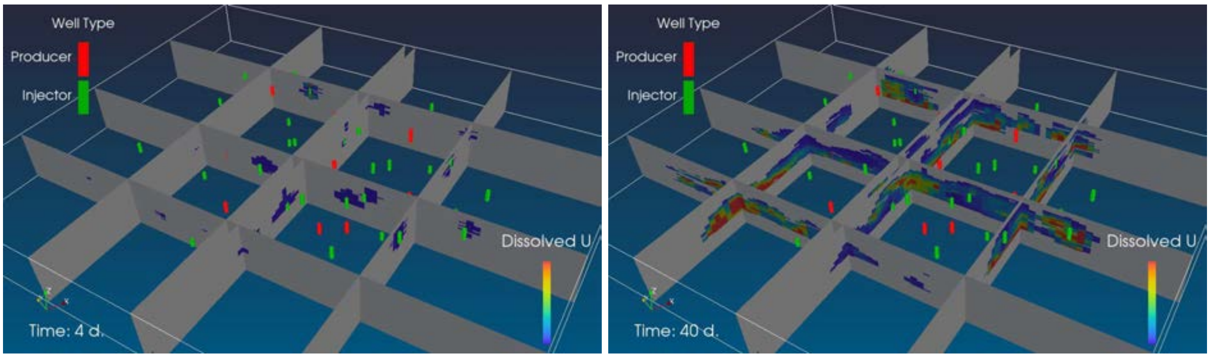

FIG. 4. Dissolved uranium in the block (4 and 40 days).

3.3. Simulation of the production

The 3–D reactive transport simulation gives a map of concentrations for all species and elements over the grid and for each time step. The information can be used to reconstruct the evolution of the fluid composition at each production well: mixing of the fluid at each cell over the height of the screens. This information is comparable to the data usually available for an ISL operator: U concentration, pH and other elements concentrations. Also, the overall balance can be calculated, and yields the block acid consumption.

The simulation of the block considered in this study fits correctly with operation data, both in terms of produced uranium and acid consumption (Fig. 5). Some parameter adjustment was necessary to obtain this good agreement between simulation and production data. However, it should be stressed that the number of fitting parameters is very small: concentrations of carbonate and iron oxi–hydroxide and reactive surface area for the smectite.

4. DISCUSSION

As demonstrated above, reactive simulations of ISL exploitation at the block scale can be performed with good results. Simulations rely on a large number of nodes grids (several 100 000s), but can be carried out in reasonable calculation time (under 24 h for a 3-year simulation).

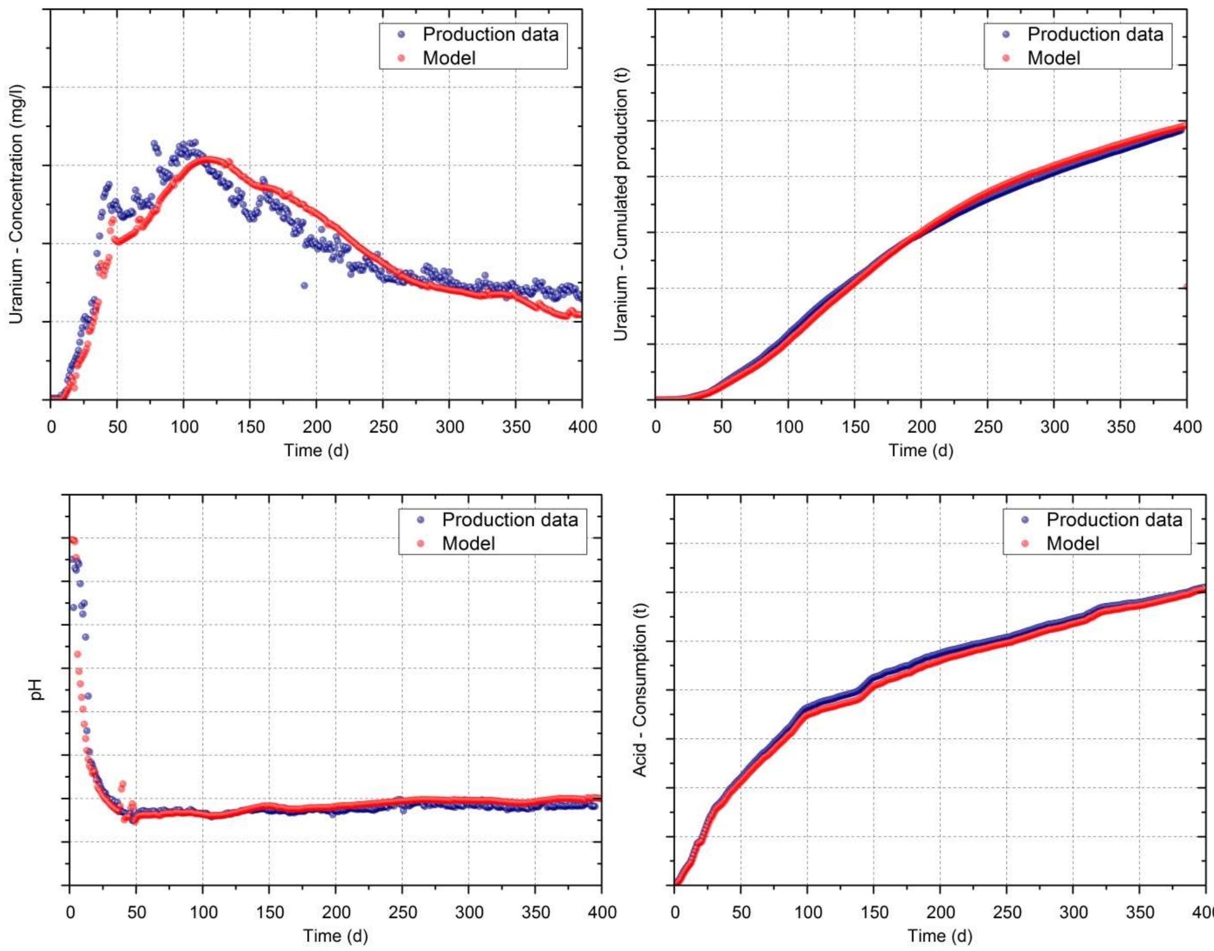

FIG. 5. Comparison of simulation results and production data at the block scale (mixing of the production wells). Top: uranium concentration (left) and cumulative production (right); Bottom: pH (left) and acid consumption (right).

Simulation results give interesting results, notably a better and quantitative understanding of the processes. Also, the simulations allow a quick identification of poor matches between local leaching rate and uranium grade. Finally, the results can be expressed in an operator-friendly format (uranium production curves and acid consumption) that can be directly compared to field data.

It should be stressed that the spatial variability of the ore body (permeability, facies distribution and uranium grade) are fundamental to accurately represent the production curves. Thus, 3–D simulation is unavoidable and a good quality block model is required. The sensitivity of the results to the block model (geostatistical realization) is moderate, at least at the block scale.

The model is robust. This is due to its process-based approach (as opposed to empirical fitting laws), and the large amount of data available to constrain the model (mineral solubility, geometry and so on). Some fitting parameters remain. However, their number is greatly reduced as mentioned above. These parameters should be adjusted from one spot in the ore body to the other. However, they seem to be uniform locally, so that a geochemical parameter adjusted in a block can be straightforwardly used in the surrounding blocks. As a result, the simulation was used predictively and accurately on several blocks, after a first adjustment on the first block produced in the zone.

5. CONCLUSION

Today, HYTEC simulation at the block scale is a semi-mature technology. Although still a R&D program, its starts to migrate towards operational needs. As stated before, some predictive simulations are performed, with some reservations. The foremost application is the qualitative comparison between exploitation scenarios, e.g. well field geometry, possibility of redrilling, modification of the acidification scenario, possible use of additional reagents (including oxidizers) and end-of-life management. The simulation results can be used to optimize the production, along different factors such as U yield, overall recovery or minimization of production costs.

ACKNOWLEDGEMENTS

The authors would like to thank KATCO for supporting this work and for fruitful discussions.

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HISTORY OF THE URANIUM MINING AND REMEDIATION EXCHANGE GROUP (UMREG)[13]

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Abstract

The Uranium Mining and Remediation Exchange Group (UMREG) was founded in 1993 from a series of meeting between experts from Governments of the USA and Germany who shared a common challenge in having to deal with the remediation of uranium production facilities that were, in part, a legacy of the Cold War era. Before too long it became apparent that other nations shared the same remediation issues and so the group became more international. In time the meetings included some of the Central Asian countries where uranium processing had been abandoned after 1989 at the time of the dissolution of the former Soviet Union. UMREG had no permanent source of funds and the meetings were often held as adjuncts to other, major, technical meetings and conferences. The association between UMREG and the International Atomic Energy Agency (IAEA) has been a long one and has resulted in two important outcomes: the production of a monograph of selected UMREG papers, published in 2011; and the incorporation of UMREG into the program of the Agency's uranium production cycle activities within the IAEA Department of Nuclear Energy. The history and plans of UMREG are briefly set out in the paper.

1. HISTORY

The Uranium Mining and Remediation Exchange Group (UMREG) was created in 1993 in the course of a bilateral meeting between two teams of experts of the US Department of Energy and the German Federal Ministry of Economics. Both groups were dealing with the remediation of uranium mill tailings and other elements of former uranium production facilities in their respective homelands. Initially meetings between the two groups related to regulatory matters but it soon became apparent that there was an opportunity for exchange and development of ideas and lessons learned that could only be beneficial to all parties.

Following the initial bilateral meetings in 1993 (Albuquerque, USA) and 1994 (Chemnitz, Germany) it was decided to expand the group and to include other major uranium production countries and so South Africa and Canada were invited to attend the 1995 meeting held in Sudbury, Canada. Australia and France began attending with the meeting in 1997 (Vancouver, Canada) and the pattern of meetings became established. Over the next years the meetings of UMREG were associated with both the Uranium Mining and Hydrogeology conference series held at the TU Bergakadamie in Freiberg, Germany (2002, 2005, 2008, 2014) and the International Conferences on Environmental Management (ICEM) organized by the American Society of Mechanical Engineers in Bruges (2001, 2007) Oxford (2003) and Liverpool (2009). There has always been a strong association with the WISMUT GmbH company which is responsible for remediation of the former uranium mining activity in the regions of Saxony and Thuringia in Germany. UMREG has been associated with the technical meetings held in Germany by WISMUT in Schlema (2000 and 2015) and Gera (2007). A brief history of the group was published by the Australasian Institute of Mining and Metallurgy in 2014 [1].

2. INVOLVEMENT OF THE IAEA

In 2007 UMREG was invited to present to the members of the OECD–NEA/IAEA Uranium Group on the occasion of their meeting at the IAEA Headquarters in Vienna. It was agreed at

[13] Based on a paper first presented at the Technical Meeting of the UMREG in Dolni Rozinka, Czech Republic, September 2013 (updated in 2015).

that meeting that the group would help promote the activities of UMREG and that the 2007 edition of the 'Red Book' would include a description of the group's activities [2]. A year later, in 2008, the IAEA offered to consider a more formal cooperation arrangement between UMREG and the IAEA which eventually began with a joint meeting of UMREG with the IAEA's ENVIRONET Group in Vienna in 2012. The cooperation extended into a full UMREG meeting held under IAEA auspices in the Czech Republic in 2013, followed by Freiberg in 2014 and Bad Schlema in 2015 (both the latter in Germany).

A further extension of the IAEA working in association with UMREG was the publication by IAEA, in 2011, of a compendium of selected papers from earlier UMREG meetings. The monograph contains 28 papers and was published as a CD, as well as being downloadable from the IAEA web site, and contains an overview of the activities of UMREG up to 2007 [3]. This current volume constitutes a second monograph including papers based on presentations at meetings from 2012 to 2015.

3. CREATION OF UMREG INCORPORATED AND THE FUTURE

A further development was formalized at the 2014 meeting, following a decision by some of these attending earlier meetings to formalize the group with the incorporation of a not-for-profit society to be known as UMREG Incorporated. This group is incorporated in the Northern Territory of Australia and has a web site which hosts various information sources related to the history and activities of members over the years (http://umreg.net/). The newly organized group is not an official IAEA associated body or activity, although it has similar aims and will continue to support the IAEA–UMREG programme as well as organizing activities of its own.

UMREG Inc. and IAEA–UMREG expect to continue to work together to promote leading practice in the development, operation and remediation of uranium mining in a balanced manner throughout the world. It is hoped that the annual meetings programme of both will continue with the 2016 meeting being planned to take place in the United States of America.

ACKNOWLEDGEMENTS

UMREG was initiated by R. Lightner (US Department of Energy) and D. Mager (German Federal Ministry of Economics). In recent years a driving force has been from A. Jakubick (retired from Wismut GmbH), with support from the author and D. Metzler of the US DoE. The cooperation of many organizations and conferences that have hosted UMREG events in addition to the IAEA is also acknowledged, in particular the Bergakadamie of the University of Freiberg and Wismut GmbH of Germany, and the American Society of Mechanical Engineers (ICEM (International Conference on Environmental Management) series of meetings).

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URANIUM MINING REGULATION AND LEGACY SITE REMEDIATION FUNDING IN AUSTRALIA'S NORTHERN TERRITORY[14]

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Abstract

The regulation of uranium mining in Australia's Northern Territory (NT) is a complex system controlled primarily under the NT Mining Management Act but with a number of additional processes and procedures involving the major stakeholders in a consultative manner, some of which are site specific. The process has developed over many years to the present state where it may be considered a mature and efficient system. The paper briefly updates the present state of regulation and recent developments at the Ranger Uranium Mine before describing the work under way to deal with uranium mine legacy sites in the NT. The paper also details a recent change to the legislation which is designed to fund a legacy mines unit and the proposed programme of works for that unit, including work in relation to former uranium mine sites.

1. INTRODUCTION

The mining of uranium has long been a matter clouded by a range of emotional and political issues which have tended to focus on certain risks rather than taking a holistic view of what is, essentially, just another example of metalliferous mining. The regulation of uranium mining has therefore been an area which has, of necessity, been obliged to develop leading edge techniques and processes in order to facilitate the industry's development while simultaneously ensuring that the highest levels of environmental protection and safety are employed. This is nowhere more apparent than in relation to the Ranger Uranium Mine (RUM), operated by Energy Resources of Australia (ERA) which is sited in a unique location, completely surrounded by the World Heritage listed Kakadu National Park. There has also been historical uranium mining within the boundaries of Kakadu and elsewhere in the Alligator Rivers region as well as other parts of the 'Top End' of the Northern Territory, including around the Pine Creek geosyncline and the Westmoreland area on the Queensland border. Some of these former mines have been remediated and some are awaiting remediation as legacy sites programme.

2. URANIUM MINING AND REMEDIATION IN THE NORTHERN TERRITORY

Australia's Northern Territory has a significant history of uranium mining which essentially began after 1945 with the operations at Rum Jungle from 1949 until 1958 [1]; this was followed by the mines of the South Alligator Valley (1953 to 1964) which together marked what may be regarded as the 'first phase' [2]. Exploration recommenced in the late 1960s resulting in four significant discoveries in the Alligator Rivers region with two new operations commencing after the introduction of the Commonwealth Government's *Environment Protection (Impact of Proposals) Act* in 1974. The two mines were Nabarlek in 1979 and Ranger in 1980; the two remaining prospects were Jabiluka and Koongarra. Ranger was the subject of a major environmental inquiry [3]. These two mines may be considered the 'second phase'.

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[14] Paper first presented at the Technical Meeting of the UMREG in Dolni Rozinka, Czech Republic, September 2013 (updated in 2015).

The third, most recent, phase of mining development is represented by the projects at Jabiluka and Ranger Three Deeps, neither of which has progressed beyond the early stages of feasibility studies despite considerable resources being expended in underground works at both sites. Neither project has received the support of Traditional Aboriginal Landowners; consequently, neither has undertaken final environmental assessment or received approval. All new mining projects in Australia are required to undergo the most stringent processes of environmental impact assessment (EIA). All uranium mining projects begun in Australia since 1974, the date of introduction of EIA legislation, have had to provide details of their remediation plans before being given approval to proceed. Also, the wishes of stakeholders and landowners now have a greater influence on the assessment processes than at any earlier stage in the industry's history. For this reason, the involvement of, and consultation with, Aboriginal Traditional Owners at all stages of the mining cycle has become a major activity for both operators and regulators from the early stages of exploration, through development and operations and into remediation and long term stewardship.

The legislation has also been updated with the development and/or remediation of any uranium mine now included as a designated nuclear activity under the Federal Government's *Environment Protection and Biodiversity Protection Act* (1999) which replaced the former EIA legislation. This designation also applies to legacy site remediation at former uranium mine locations.

3. HISTORICAL URANIUM MINING OPERATIONS

3.1. Rum Jungle

Although mining for copper began at the site in 1905 uranium was not identified at Rum Jungle until 1912 but no mining took place [1]. Following the 'discovery' of a significant deposit by Jack White in 1949 uranium mining was undertaken by the Australian Government from 1954 until 1958, while copper mining continued until 1965 with the mine finally closing in 1971. The uranium was mined specifically on behalf of the Australian Commonwealth (Federal) Government and, as there was no legal requirement to remediate the site, it was simply abandoned. There was a number of environmental issues as a result: infrastructure and machinery decaying all over the site; tailings inadequately contained and washing into the Finniss River; and substantial amounts of metals and other pollutants being released into the Finniss River as a consequence of sulphides in the stockpiles oxidizing to release acid metalliferous drainage (AMD). An initial cleanup operation undertaken in 1977–78 was not wholly successful, establishing some revegetation, but completely ignoring the issue of AMD and the associated pollution from the waste stockpiles [1].

By 1980, public concern about the impacts of the mine on the Finniss River (virtually devoid of aquatic life for about 14 km downstream of the site) and the Commonwealth Government funded a remediation program which was undertaken on its behalf by the Northern Territory Government. The program ran from 1982 until 1986 and cost AU $18.6M [4]. The major objectives of the program [1] 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;
- 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 requirement, or intention, that the site should be rehabilitated such that the public could have unrestricted access. In the programme tailings were relocated and contained, waste rock was encapsulated in new landforms designed 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 thus significant management was required to maintain the vegetation cover. The result was a site quarantined from any future use and which required ongoing management for the remediation to remain effective.

Such outcomes are not acceptable today when modern communities expect former minesites to be restored to some form of 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 [5]. The programme was completed but the results have proved to be unsustainable. The failure of the remediation works to meet the objectives in a sustainable way has resulted in further works being required. Again, action is being taken following renewed public concern about the adverse environmental impacts of former mining activity.

3.2. South Alligator Valley mining field

Between 1955 and 1964, thirteen small uranium mines, two small processing sites and a mill operated in the South Alligator Valley. All the operations were simply abandoned at the end of mining [2]. No remediation action was undertaken until the mid-1980s when the valley was designated to become a part of Kakadu National Park. In 1986, tailings were removed from the mill site to a location outside the Park and processed to extract gold. Between 1990 and 1992, the Commonwealth Government undertook a program of works at all the mine sites, including the mill, with the objective of reducing radiological and physical hazards for park visitors and traditional landowners to levels compatible with the new land use [2]. In 1996, following the successful outcome of a native title claim the land was handed back to the traditional owners. They in turn immediately leased back the area so it could remain as a National Park. The lease required that all mine sites be fully rehabilitated by 2015. A long programme of negotiations with Aboriginal Traditional Owners and design studies over several years culminated in a successful remediation strategy being developed [6]. Remediation work at the first two sites was completed in 2007 and the whole programme was completed in 2009 [7]. A major objective of the remediation was to ensure that the sites blend in with the surrounding countryside would not require any special management. Monitoring continues at the present time with no planned end to the programme [8].

4. CURRENT AND RECENT URANIUM MINING OPERATIONS

4.1. Ranger uranium mine

Ranger is the only uranium mine currently operating in the Northern Territory. It was a conventional open cut operation with two pits; Pit 1 operated from 1980 to 1995 and Pit 3 which was operated from 1997 until 2013. Pit 1 was filled with tailings and Pit 3 is the active tailings repository, there is also a large tailings dam approximately 1 square kilometre in extent. Under the current working arrangements ERA is required to cease mining and processing activity early in 2021 and commence remediation which is due to be completed in 5 years. 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;
— Implementation of progressive remediation wherever possible.

The remediation plan for 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 ERA 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 [9]. The overall objective for the project area is to be remediated and to establish an environment which reflects that existing in the surrounding area and would permit the incorporation of the former site into the surrounding Kakadu National Park without detracting from the Park values or needing special management.

ERA is required to revise the remediation plan annually for approval by the Supervising Authorities in consultation with the main stakeholders. The plan has to be sufficiently detailed for stakeholders to be confident that the goal and objectives would be met should the plan need to be implemented during its lifetime. The detail provided should be sufficient to enable a comprehensive costing to be made. The mining company is then required to deposit an appropriate financial security with the Australian Government that would be sufficient to pay for the implementation of the approved plan. The security is provided in the form of cash and approved bank guarantees. A complete blueprint for the total decommissioning of the site is currently being prepared by ERA, this will include the detailed completion criteria. In the ERA Annual Report for 2014 the company announced a provision of AU $512 million had been made in the company accounts for all rehabilitation works and it should be emphasized that this sum covers all the costs such as social charges, worker payments and entitlements, not only the physical works costs used to compute the remediation security.

4.2. Nabarlek uranium mine

Nabarlek is the most recent example of a modern uranium mine remediation in Australia [10]. The ore body was discovered in 1973 and its development was subjected to what was then considered intense scrutiny through a public inquiry [3] and an EIA process [11]. The ore body allowed mining to be completed in one dry season in 1979 and the ore was stockpiled while the mill was built. Milling continued until 1989 when the site was 'mothballed' for 5 years while the mining company explored for new reserves. In 1994 the regulating 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 [10, 11].

Criteria for successful remediation included a requirement 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. 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 [10]. Enhanced planting of seedling trees raised from local provenance seed was used to improve the situation and was looking successful but the whole region was severely impacted by a cyclone in 2006 which has set back tree establishment and growth considerably. The enhanced planting programme was reinstated and a new period of observation begun. The ownership of the mineral lease has changed hands which has further complicated efforts to achieve a satisfactory outcome. The physical earthworks are complete apart from one small anomalous area but the main issue is still getting agreement from all parties as to what will constitute success in remediation. Current expectations are high and the stakeholder group, which includes regulators and landowners, is requiring that the sustainable establishment of an 'appropriate' climax vegetation association be adequately demonstrated before the mining company can be released from its obligations for the site [10].

5. OTHER IDENTIFIED URANIUM MINING PROJECTS

5.1. 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 finally completed in 2013 and revegetation works are ongoing, together with an approved surveillance and monitoring programme.

5.2. Koongarra

The Koongarra project was identified in the 1970s but no development took place as the Aboriginal Traditional Owners would not give their approval. In 2011, the World Heritage Committee accepted the recommendation of the Australian Government and incorporated the project area into the Kakadu World Heritage Area. Subsequent legislative changes allowed for the incorporation of the mining area into Kakadu National Park and this action was completed in March 2013. The EPBC Act precludes any mining developments within Kakadu National Park and thus the project is now considered to be ended.

6. REMEDIATED URANIUM MINING PROJECTS

6.1. South Alligator Valley mining field

Between 1955 and 1964, thirteen small uranium mines and a mill operated in the South Alligator Valley. All the operations were simply abandoned at the end of mining. No remediation action was undertaken until the mid-1980s when the valley was designated to become a part of Kakadu National Park. In 1986, tailings were removed from the mill site to a location outside the Park and processed to extract gold. Between 1990 and 1992, the Commonwealth Government undertook a program of works at all the minesites, including the mill, with the objective of reducing radiological and physical hazards for park visitors and traditional landowners to levels compatible with the new land use [4]. In 1996, following the successful outcome of a native title claim the land was handed back to the traditional owners. They in turn immediately leased back the area so it could remain as a National Park. The lease required that all mine sites be fully rehabilitated by 2015. A long programme of negotiations with Aboriginal Traditional Owners and design studies over several years culminated in a successful remediation strategy being developed [6]. Remediation work at the first two sites was completed in 2007 and all work was completed in 2009 [7]. A major objective of the remediation was to ensure that the sites blend in with the surrounding countryside would not require any special management.

7. CURRENT REGULATORY PROCESS

All mining in the Northern Territory (NT) is governed by the Department of Mines and Energy through the *Mineral Titles Act* (MTA) and the *Mining Management Act* (MMA); these two instruments deal with land tenure for mining and environmental management and protection in mining respectively. Other NT Government agencies also have a part to play such as NTWorksafe for worker health and safety matters, the NT Environment Protection Agency in issuing off-site water discharge licences and the Department of Health in terms of the National Dose Rate Register for uranium mining workers.

7.1. Routine regulatory and remediation security process

For all mining operations there has to be an initial grant of a title for the area of land which would normally be a mineral lease issued under the MTA although in the case of RUM this is a special Project Area under s.41 of the AEA. Once the title is granted the operator submits a Mining Management Plan (MMP) for assessment and approval under the MMA. The MMP should include all the background information on the project including all environmental data, heritage and endangered species data, management plans for all aspects of the operation and in particular details of works planned for the next 12 months or whatever period of time has been set by the regulator. Once the MMP has been approved the operator is required to calculate the estimated cost of remediation for all the works set out in the MMP, including a 15% contingency allowance. This is done using a calculation tool, in the form of spreadsheets, provided by the DME [12]. A check calculation by DME is completed and the final sum determined with the assistance of the Securities Assessment Board, which contains independent members, if necessary. The security amount is deposited with the DME as either cash or an unconditional bank guarantee from an appropriate, Australian-licensed, financial institution. Once the security has been lodged and accepted then the authorization to commence mining is signed and issued. This system has been in place since 2006 and is now well established and regarded as one of the strongest regulatory mining security systems in Australia. In 2005, the DME held approximately AU $38.2 million as security against the liability of all operational mines in the NT. In October 2015, the DME was holding AUD$1.34 billion for the same liability and it is possible that may be an underestimate of the total liability for authorized operations depending on timing of submissions and payments.

7.2. Regulation of uranium mining in the Alligator Rivers Region

In the case of uranium mining within the Alligator Rivers region (ARR) there are additional specific conditions which require the participation of the Australian Government (AG): The primary regulator is the DME through the MMA, however various other groups are involved. The AG Department of Industry administers the *Atomic Energy Act* (AEA) which governs the title for the area of land that RUM is located on and the issue of export licences for uranium; The AG Department of the Environment supports the Supervising Scientist who is appointed to oversee the environmental protection of the Kakadu National Park from the possible effects of uranium mining; the Northern Land Council, an organization funded by AG, acts on behalf of Aboriginal Traditional Land owners under the *Aboriginal Land Rights Act*. There is also involvement of the AG's Australian Safeguards and Non-Proliferation Office in relation to various international treaties. Finally, there is representation on the Minesite Technical

Committee at RUM from the Mirrar people, the specific Aboriginal Traditional Owners of the land in which RUM is located.

There are also two permanent committees facilitated by the Supervising Scientist. The Alligator Rivers Region Advisory Committee meets twice per year to provide a forum for information exchange between all the major stakeholders and various community groups, mining companies and government departments. The Alligator Rivers Region Technical Committee also meets twice per year and is a panel including independent scientists and experts as well as research organizations, regulators and the mining companies and is charged with oversight of scientific research in the region in relation to assessment and mitigation of environmental impacts that might arise from uranium mining.

The Minesite Technical Committee (MTC) for each uranium mine meets at appropriate intervals dictated by the level of activity in each project to discuss the current state of activity on each site and to debate new projects as a form of pre-approval process. This system also provides a forum for discussion of both long and short-term monitoring data as well as any other issues that stakeholders may wish to debate in relation to environmental management and protection at the mines. The parties comprising the MTC also attend monthly inspections at the RUM site and conduct an annual environmental audit. The same group also undertakes inspections and audits at the various uranium exploration operations within the ARR and at the remediating Nabarlek minesite.

7.3. Legacy mines and funding

The issue of legacy mines has been a major concern for many regulators for a long time and the NT is no different. A rough estimate of liability to the NT Government for existing legacy minesites in the NT alone was put at AUD$1 billion in 2012, which caused a concern among members of the government. As consequence the MMA was modified in 2013 to allow for the creation of a Mining Remediation Fund which would be the recipient of a levy on mining securities. Since 1 October 2013, the MMA has established that the levy is an annual payment to be made by every holder of a mining authorization issued under the MMA. The amount of the contribution for an authorization holder is calculated as 1% of the total security held for that authorization either on 1 July each year or, in the case of new projects, pro–rata for the remainder of the year until 30 June. Payments are invoiced in the third quarter of the calendar year and must be made in cash within 30 days of the invoice. In accordance with the purpose of the fund set out in the MMA, monies received must be used by the DME "in connection with minimizing or rectifying environmental harm caused by unsecured mining activities".

To this end, the fund has been used to set up a Legacy Mines Unit (LMU) within the Remediation Division of the Mines Directorate of DME. LMU has been operational since late 2013 and immediately began work to create an inventory of legacy mine sites throughout the NT with the intention of providing a list of priority sites that would form the basis of the initial work programme. To date the LMU has undertaken a variety of small scale works ranging from safety issues where abandoned mine shafts in public recreation areas have been backfilled to longer term studies of complex AMD problems at older sites and preparation of plans for works designed to maintain conditions on a site until sufficient funding can be found to complete larger scale works. Some staff of the LMU had previously worked in a number of uranium related sites, including the South Alligator Valley mentioned earlier.

7.4. Long term monitoring and stewardship

A significant issue that remains unresolved is the stewardship or long term care of remediated uranium mine sites [13]. There is a real concern that systems currently in place at present may rely too much on institutional controls in order to remain effective over the long term. A lot of people consider that former uranium mine sites should 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. It may also be that long term or even perpetual management of some situations (e.g. water treatment at severely impacted AMD sites) has to be considered. The major elements of stewardship are: (1) appropriate monitoring and surveillance for as long as required (in perpetuity if necessary); (2) provision of maintenance as required; (3) ability to undertake further remedial actions if needed; and (4) communication and consultation with stakeholders. Few organizations other than national 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 remediated mine in their locality and that they really do have opportunities to contribute to decision making, especially throughout the stewardship period. The ultimate goal of stewardship must be to ensure that environmental protection is paramount and maintained at the required level for the time required, again perpetuity if necessary.

8. FUTURE PROSPECTS AND CONCLUSIONS

From the time the material in this paper was originally presented (2013) to the date of publication (2016) much has happened in the NT's uranium mining industry. The failure of a leach tank at RUM in December 2013 led to a six-month shutdown enforced by the regulator; this severely tested the relationships between all stakeholders and had significant commercial ramifications. The failure of ERA to obtain support from both its major shareholder and the Aboriginal Traditional Owners has resulted in the shelving of the Ranger Three Deeps project which in turn has led to the current situation that operations will now cease in 2021 and remediation planning will be targeting 2026 as the completion date for all significant works. In other parts of the NT some of the smaller uranium prospects are not moving development forward due to the state of the current and predicted markets.

But, the same time not all the news about uranium is negative. Cameco of Canada has made an interesting initial discovery in West Arnhemland and are progressing their studies and activities steadily. Some minor players are continuing to explore in the more prospective areas saying that they intend to be ready when the market changes direction again. This could be within 5–10 years and as most new uranium prospects seem to be taking about 10 years to reach the operational stage such planning may not be too far from a practical reality.

It is more than likely new prospects will be found and new mines will develop, but it is not going to be soon. The remediation and post-closure stewardship of RUM will be a process that will involve many people from the uranium mining industry for quite a few years to come, be they regulators, operators or other stakeholders. The nuclear 'renaissance' of the early 2000s and 2010 has passed by and in a post-Fukushima world the community in many areas is slowly returning to the idea that nuclear power has a place as a part of a lower carbon future for energy programmes. That means that uranium mining will also have a role to play going forward and the NT intends to maintain its position in that part of the industry.

ACKNOWLEDGEMENTS

The author wishes to thank his colleagues in the DME and other professional associates for their counsel and discussions during the preparation and internal refereeing of this paper.

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AN OVERVIEW OF IN SITU LEACH URANIUM MINING AND ASSOCIATED REMEDIATION ISSUES[15]

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Abstract

Following early experimentation and production in the 1960s, in situ leach (ISL) mining has become one of the standard uranium production methods. Its application to amenable uranium deposits (in certain sedimentary formations) has been growing in view of its competitive production costs and low surface impacts. ISL uranium mining has gained widespread acceptance and its share in total uranium production grew from 13% in 1997 to 46% in 2011. The IAEA has prepared an overview report to show how ISL experience around the world can be used to direct the development of technical activities, taking into account environmental considerations and an emphasis on the economics of the process, including responsible mine closure. With this report Member States and interested parties will have more information to design and efficiently and safely regulate current and future projects, with a view to maximize economic performance and minimize negative environmental impact. Highlights of the report's findings are provided here, with a summary of the IAEA's involvement in ISL over recent decades and some discussion on ISL remediation issues.

1. INTRODUCTION

In situ leach (ISL; also called in situ leaching or in situ recovery, ISR) mining has become one of the standard uranium production methods, following early experimentation and production in the 1960s. In 1997 the percentage of ISL operations compared to other conventional forms of uranium mining was 13%; by 2009 it had grown over 30%, reaching 46% in 2011. In the past, the method was applied mainly in Ukraine, the Czech Republic, Uzbekistan, Kazakhstan, Bulgaria and the United States of America (USA). Recently it has continued to be used in Kazakhstan, Uzbekistan and the USA; it has also been applied commercially in Australia, China and the Russian Federation, with small operations or experiments elsewhere.

In the IAEA report discussed here [1], ISL is referred to as a special form of solution mining applied to ore deposits in sedimentary, saturated aquifers by using injection and extraction wells from the surface. Mining solution — acidic or alkaline, depending on the mine — is circulated through the orebody, dissolving uranium and some other mineral constituents but leaving the bulk of the aquifer material behind. Uranium is recovered from the mining solution in a processing plant, and the solution reconditioned and recirculated through the orebody. This process is repeated many times before a particular block of ore is mined-out. The report and this paper do not include detailed consideration of any kind of leaching in unsaturated formations or of block leaching in underground mine works (e.g. [2]).

2. EARLIER IAEA ISL REPORTS

The IAEA began publishing ISL specific reports in 1979. These, and some others where ISL was a significant part, are listed in Table 1 with footnotes for those that are proceedings of a meeting. There are also many individual papers on ISL uranium mining in other IAEA reports and proceedings not shown here. Individual papers from some of the listed reports and other IAEA proceedings are cited later in this paper.

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[15] Presented at the UMREG 2013 meeting, Dolni Rozinka, Czech Republic (updated 2015).

TABLE 1. EXISTING IAEA REPORTS WITH SIGNIFICANT INFORMATION ON ISL URANIUM MINING

Year	Title	Series	Reference
2005	Guidebook on environmental impact assessment for in situ leach mining projects	TECDOC–1428	[3]
2004	Recent developments in uranium resources and production with emphasis on in situ leach mining[16]	TECDOC–1396	[4]
2002	Working Material In Situ Uranium Mining[17]	WM–T1–TC–975	[5]
2001	Manual of acid in situ leach uranium mining technology	TECDOC–1239	[6]
1997	Environmental impact assessment for uranium mine, mill and in situ leach projects	TECDOC–979	[7]
1993	Uranium in situ leaching[18]	TECDOC–720	[8]
1992	New developments in uranium exploration, resources, production and demand[19]	TECDOC–650	[9]
1989	In situ leaching of uranium: technical, environmental and economic aspects[20]	TECDOC–492	[10]

3. NEW IAEA ISL REPORT

3.1. Report structure

The table of contents of the IAEA's new ISL report "In Situ Leach Uranium Mining — An Overview of Operations" [1] is summarized in Table 2.

[16] Proc. Tech. Mtg, Beijing, China, 18–23 Sep. 2002.
[17] Proc. Tech. Comm. Mtg, Almaty, Kazakhstan, 9–12 Sep. 1996.
[18] Proc. Tech. Comm. Mtg, Vienna, Austria, 5–8 Oct. 1992.
[19] Proc. Tech. Comm. Mtg, Vienna, Austria, 26–29 Aug. 1991.
[20] Proc. Tech. Comm. Mtg, Vienna, Austria, 3–6 Nov. 1987.

TABLE 2. SUMMARY TABLE OF CONTENTS OF THE MOST RECENT IAEA ISL REPORT [1]

Section	Title	Notes
1	Introduction	–
2	Terminology and conversion factors	The chapter describes the definition of resources and reserves in international schemes and the schemes of Australia, the Russian Federation (used in some former Soviet Republics and affiliated countries) and the USA. Conversion factors are listed after references.
3	Fundamentals	Definitions, conditions of application, recovery technology, satellite mining, groundwater remediation, above ground decommissioning
4	Historical developments	By country, alphabetically listed
5	Political and social framework	Regulatory regimes in Australia, Kazakhstan and the USA; political/sovereign factors
6	Compilation of project data	List of projects, production statistics, potential future ISL countries
7	Outlook	Future of ISL, key factors, economics and markets, technology, environmental management
References, glossary, conversion factors and list of abbreviations		178 References
Annexes	58 individual deposits or grouped deposits, arranged by country in alphabetical order	Where available, lists associated company names, location, operational statistics, geology, production technology and parameters and restoration approach

3.2. Report highlights

3.2.1. Conditions of ISL applications

ISL uranium mining is not possible or economic in many uranium deposit types. To date, its application is restricted to sandstone-hosted uranium deposits [11]. The following is reproduced from the report [1], where further discussion and description is provided.

"The following major conditions are necessary in order to apply the ISL method of mining uranium[21]:

[21] Some experiments or operations only partly satisfy conditions 1 and 4, requiring special considerations and adaptations to the common ISL technologies described in the IAEA report [1].

1) Water saturated aquifer host formation with a water head high enough for a stable hydraulic pumping regime;
2) Sufficient permeability of the host formation to circulate mining fluids (usually dominated by sand or sandstone);
3) The ability for multiple recycling of the leaching solution through the ore formation;
4) Confinement of the host formation (aquifer);
5) Leachability of the mineral matrix containing uranium, in particular low abundance of interfering minerals or other constituents;
6) Disposal system for wastewater and other residues".

The relatively low environmental impact and capital requirements of ISL uranium mining makes the method attractive for mining operators (see next section). However, its application is limited to suitable deposits and there have been failed attempts. As well as geological investigations to ascertain the presence, grade, geometry and size of a potentially ISL-amenable uranium orebody, significant hydrogeological testing is required [12]. This may extend to trial mining (ibid.). The IAEA report [1] includes some examples of unsuccessful attempts at ISL uranium mining, as well as many successful examples.

3.2.2. Environmental protection aspects

Is it generally recognized that ISL uranium mining technology has environmental (and safety) advantages compared to conventional uranium mining and milling [3], although there are some cases of significant environmental impact to groundwater (see Section 3.2.3). Its major environmental advantages over conventional uranium mining are that no tailings or waste rock are generated and that physical land disturbance (i.e. its footprint) is small. General guidelines for environmental protection associated with ISL have emerged (e.g. [3, 7, 13]).

The main potential negative impacts of ISL mining include:

— Movement of mining or waste solutions beyond the target zones, especially when local groundwater has other users, or likely users;
— Leakage from pipes transporting mining solutions, spills of transported resin when satellite mining is involved;
— The residual risk in mined-out aquifer, especially the water quality after mining and its possible migration away from mining areas;
— Possible groundwater consumption issues due to bleed (see later text) or other groundwater consumption, especially in semi-arid and arid areas where there is limited availability of water supplies;
— General environmental and health risks due to industrial-scale mineral processing and transport.

Many environmental and safety problems can be eliminated, or at least minimized, during mechanical and metallurgical design and through good quality control of materials and construction activities. This includes the sealing of the outside of well casings to prevent inter-aquifer contamination, often with pressure testing of wells to demonstrate their integrity. The possibility of additional industrial chemicals, fuels or processing materials (e.g. hydrocarbons when solvent exchange technology is employed, or wastes generated during processing) returning to the mined aquifer with recirculated mining solution should also be eliminated or the risk greatly reduced. However, a valid and permitted means of disposal of liquid and solid wastes is essential, either off- or on-site.

During operations, in many cases a small bleed is maintained, i.e. the overall rate of extraction of mining solution and groundwater is slightly greater than extraction; this maintains an inward hydraulic gradient towards the active mining areas (wellfields), reducing the risk of the migration of mining solution outside the target zone. A suitable means of disposal of this surplus, which may vary from less than one to a few per cent of the total pumping rate, must be available. Protection against surface spills from pipes and ponds should also be provided, by good preventative maintenance, frequent visual inspections, electronic alarms (e.g. for sudden loss of pressure, pond levels reaching a threshold, leak detectors in spill catching tanks), and rapid response and repair when leaks do occur.

During decommissioning and rehabilitation, the following measures are typically taken:

- Permanent sealing of wells to prevent inter-aquifer contamination (other than monitoring wells maintained after operations);
- Re-establishment of natural or designed groundwater hydraulic gradients;
- An approved decision between an active versus a passive approach to the management of residual mining and disposal fluids;
- An approved decision between an active versus a passive approach to prevent contamination of nearby aquifers (if applicable);
- Surface facility rehabilitation, including ponds, pipes, unwanted roads and buildings, the processing plant and any waste disposal facilities.

The absence of waste rock piles and tailings (or spent heap leach piles) greatly simplifies and reduces the expense of the surface decommissioning and rehabilitation of ISL mines.

3.2.3. Discussion regarding groundwater remediation

The report notes that "Remediation[22] of residual mining (and in some cases disposal) solution that remains in the mined aquifer at the completion of mining may or may not be required depending on the prevailing regulatory environment, the original pre-mining quality of groundwater in the aquifer intended for mining, the known or expected end use of the aquifer, the connectedness of the mined aquifer to other groundwater resources, users or the environment, and the likelihood of migration of residual mining or disposal water".

"The requirement for or acceptance of little or no remediation other than 'monitored natural attenuation' of groundwater after ISL mining has been a major source of discussion and sometimes disagreement between miners, regulators, external stakeholders and NGOs[23]. Where remediation is required, the target water quality is also a point of discussion; should it be to meet a given use category (e.g. suitable for stock or domestic water supply, with or without further treatment) or returned to (close to) the original water quality within certain ranges?"

"Factors where groundwater remediation is more likely to be scientifically, regulatorily or socially required include:

- Groundwater in the aquifer targeted for mining is used by others in the targeted area or

[22] As defined in the IAEA safety glossary and relevant articles in the Section 5 of the General Safety Requirement Part 3 [14], with regard to radiological protection some old ISL can be treated as an existing exposure situation, for which the term remediation can be used. However, some new or younger ISL mining should be considered as planned exposure situations. For the later cases, restoration may be better word, although this may have different connotations with regard to non-radiological contaminants and so is not used here.
[23] Non Government Organizations.

nearby in the same aquifer, in a hydraulically well-connected aquifer, or where there is a non-negligible risk of adverse effects on those users;
- Original groundwater quality meets guidelines for certain uses but is not currently being used in the vicinity or from adjacent aquifers that might reasonably be adversely affected;
- Affected groundwater supports natural springs or otherwise enters surface waterways, lakes or marine environments with a non-negligible risk of adverse effects."

"Factors where remediation is less likely to be scientifically, regulatorily or socially required are:

- Groundwater in the aquifer targeted for mining is in poor or negligible hydraulic connection with surrounding aquifers;
- Groundwater in the aquifer targeted for mining is not used by others in the targeted area or nearby in the same aquifer, nor a hydraulically connected aquifer, or where there is a negligible risk of adverse effects on those users;
- Original groundwater quality does not meet guidelines for certain 'higher' uses such as domestic, irrigation or pastoral use, perhaps due to high salinity, high natural radioactivity or the natural presence of toxic elements such as arsenic or fluorine;
- Treatment of affected water may create wastes that are more problematic to dispose of safely compared to keeping the affected water in the mined-out aquifer or specific disposal aquifer;
- The geochemistry of natural sediments and rock materials surrounding the mined aquifer is such that any migrating mining or waste solutions will be neutralized and/or problematic constituents significantly retarded;
- Long pathways (time and distance) to any known or potential discharge point of the aquifer being mined."

In some jurisdictions, notably in the USA, active remediation (called restoration) of mined aquifers is a legal requirement. Many of the mined aquifers contain groundwater of sufficiently good quality for other uses, falling into the "…where groundwater remediation is more likely to be scientifically, regulatorily or socially required" category discussed above. In many cases there, demonstration of the effectiveness of a proposed restoration method is required on a trial mining scale before full-scale mining can commence. For some recent approvals in the USA, a commitment to use technology now successfully used on a commercial scale in similar deposits has been permitted, in the absence of a completed demonstration. The default round water quality target for groundwater remediation, before the site is considered restored, is close to baseline; however, in some cases this can be modified by negotiation based on achievability and other applicable factors, such as guidelines for particular uses.

Active remediation has been a feature of former ISL mining area remediation in the Czech Republic, where the circumstances again are "…where groundwater remediation is more likely to be scientifically, regulatorily or socially required". The situation has been extensively described in the literature (e.g. [15–18]). The contamination distribution was complicated by the partially cotemporary operation of an ISL (Straz) and conventional underground mine (Hamr) [19], leading to migration of acidic mining solutions well beyond the target orebody area. There was also some leakage of acidic water into an overlying aquifer containing good quality groundwater. The treatment of contaminated groundwater, to prevent its possible leakage into a river system and to reduce contamination in the overlying aquifer, started in the mid-1990s and is expected to last for some decades [16, 17].

In Australia and Kazakhstan, monitored natural attenuation is currently the planned closure strategy for mined-out aquifers, due to local circumstances and poor initial water quality. This again fits into the "… where remediation is less likely to be scientifically, regulatorily or socially required" category discussed above [20–22].

Regardless of a passive or active approach, groundwater monitoring is required, perhaps in the long term, to establish that sufficient forced or natural attenuation is occurring in a reasonable timescale and within a defined area of aquifer. This can then give assurance that the desired or required outcome will be reliably achieved. In the case of the Beverley ISL uranium mine in Australia, a contingency plan was required in case post-closure groundwater monitoring showed the closure objectives for groundwater were likely to be breached, although groundwater and geochemical modelling indicated natural attenuation would meet appropriate outcomes [23].

4. DISCUSSION AND CONCLUSION

The advantages of ISL uranium mining, where a uranium deposit is amenable, has contributed to its popularity and use worldwide. In general, the advantages outweigh the disadvantages, but there are some historic examples of technological or economic failure of the mining method and of unintended negative environmental effects and legacies. Hence, with any mining project, a careful and sufficiently robust feasibility study and risk analysis should be undertaken before a project commences. The issue of active versus passive subsurface remediation of groundwater on closure should be carefully considered and justified, although the choice may currently be limited to active remediation by regulation in some jurisdictions. Demonstration of the effectiveness of the containment of mining solutions during operations, and the achieving of groundwater quality goals on closure, should also feature in any project. Consideration should be given to contingency plans during operations and closure to allow additional intervention if the migration of mining solutions or impacted groundwaters could cause site specific groundwater protection and closure goals to be breached.

ISL uranium production can be expected to account for almost 50% of world production during the next few years [1]. In the longer term, however, this percentage may decrease, as more high-grade deposits in Canada and additional low-grade heap leach deposits in Africa (and elsewhere) could be brought into production. Nevertheless, the IAEA report [1] suggests that ISL will continue to be a very significant component of world uranium production for the foreseeable future.

The same report concludes: "[I]n summary, safety, societal aspects, environmental and radiation protection and successful progressive and final rehabilitation will continue to be vital to ongoing uranium mining globally, to ISL as much as more 'conventional' mining."

ACKNOWLEDGEMENTS

The IAEA's "In Situ Leach Uranium Mining — An Overview of Operations" report [1] was the outcome of two IAEA Technical Meeting and three associated consultants' meetings, 2010–2013. The responsible IAEA Technical Officers for that publication are P. Woods and J. Slezak, and the other contributing authors are V. Benes (Czech Republic), O. Gorbatenko (Kazakhstan), B. Jones (Australia), H. Märten (Germany/Australia), T. Pool (USA) and I. Solodov (Russian Federation) [24]. M. Potot–Tarmann of the IAEA greatly assisted with checking and formatting the report. Only selected excerpts are highlighted here.

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REMEDIATION OF FORMER URANIUM IN SITU LEACHING AREA AT STRAZ POD RALSKEM–HAMR NA JEZERE, CZECH REPUBLIC[24]

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Abstract

A large scale development in exploration and production of uranium ores in the Czech Republic was done in the second half of the 20th century. Many uranium deposits were discovered in the territory of the Czech Republic. Over a period of 50 years approx. 110 000 tonnes of uranium in concentrate were produced. Different mining methods were developed and used. One of the most considerable deposits in the Czech Republic is the site Hamr na Jezere–Straz pod Ralskem where both mining methods (underground mining and acidic in situ leaching) were used. The extensive production of uranium led to widespread environmental impacts and contamination of ground waters. Over the period of 'chemical' leaching of uranium (approximately 32 years), a total of more than 4 Mt of sulphuric acid and other chemicals have been injected into the ground. Most of the products (approx. 99.5%) of the acids reactions with the rocks are located in the Cenomanian aquifer. The contamination of Cenomanian aquifer covers the area larger than 27 km^2. The influenced volume of groundwater is more than 380 Mm^3. The total amount of dissolved SO_4^{2-} is about 3.6 Mt. Approximately 0.5 % of the contamination is located in the Turonian aquifer. After 1990 a large scale environmental program was established and the Czech government decided to liquidate the ISL Mine and start the remediation in 1996. The remediation consists of contaminated groundwater pumping, removing of the contaminants and discharging or reinjection of treated water. The objectives of the remedial activities are described in following points: to restore the rock environment to a condition guaranteeing continuing usability of Turonian water of Northern Bohemia Cretaceous, to decommission boreholes and surface installations and to incorporate the surface of leaching fields into the ecosystems taking into account regional systems of ecological stability and urban plans. Nowadays four main remedial technological installations for reaching of these aims are used — the "Station for Acid Solutions Liquidation No. One", the "Mother liquor reprocessing" station, the "Neutralization and Decontamination Station NDS 6" and the "Neutralization and Decontamination Station NDS 10". Total capacity of this complex is sufficient to reach the target values of remedial parameters in 2037. The remediation action consists of: pumping of residual solution to the surface, separating uranium from the solution and reprocessing contaminants into commercially usable or ecologically storable products. It is expected that the amount of withdrawn contaminants will vary from 80 000 to 120 000 tonnes per year. Total costs of all remediation activities are expected to be in excess of 1.5 billion EUR.

1. INTRODUCTION

The history of uranium exploitation in the Czech Republic (and in the former Czechoslovakia) dates back more than 60 years. Over the initial period, from 1946 until the beginning of the 1950s, the exploitation was mainly carried out in the reopened mines of the Jachymov mining area. Rapid development of surveying and extracting work was reflected in the large growth of exploitation in other areas of Bohemia and Moravia. This concerned the regions Pribram, Hamr na Jezere–Straz pod Ralskem and Dolni Rozinka, i.e. southern, northern and western Bohemia. More than 100 000 tonnes of uranium had been extracted from over 800 trial and production shafts since 1946.

Owing to the diversity of the deposits, the uranium exploitation was carried out with the whole spectrum of mining methods available, which were selected as appropriate for the host rock at the given locality. In general terms, there are two basic methods of uranium extraction applied in the Czech Republic:

- Conventional underground mine workings;
- In situ leaching (ISL).

[24] Based on the papers "Remediation of consequences of chemical leaching of uranium in Stráž pod Ralskem" and "Overview of the ISL remediation at Straz pod Ralskem" first presented at the Technical Meeting of the UMREG in Dolni Rozinka, Czech Republic, September 2013 (updated in 2015).

2. URANIUM MINING HISTORY AT THE HAMR NA JEZERE–STRAZ POD RALSKEM DEPOSITS

The deposits in the area of Hamr na Jezere–Straz pod Ralskem were discovered in the 1960s. In 1963, an aerial geophysical surveying detected high magnetic anomalies into which a borehole, HJ–1 (Hamr na Jezere–1) was drilled. Following the detection of the anomaly at well HJ–1, other exploration boreholes were drilled in its vicinity and all of them confirmed uranium mineralization (e.g. [1, 2]). Well HJ–1 located in the Hamr na Jezere deposit represented the beginning of the geological exploration and borehole drilling programe. Several uranium depostis were later discovered in the Stráž tectonic block. Location of the Stráž tectonic block in the Bohemian Cretaceous Basin within the Czech Republic is shown on Fig. 1.

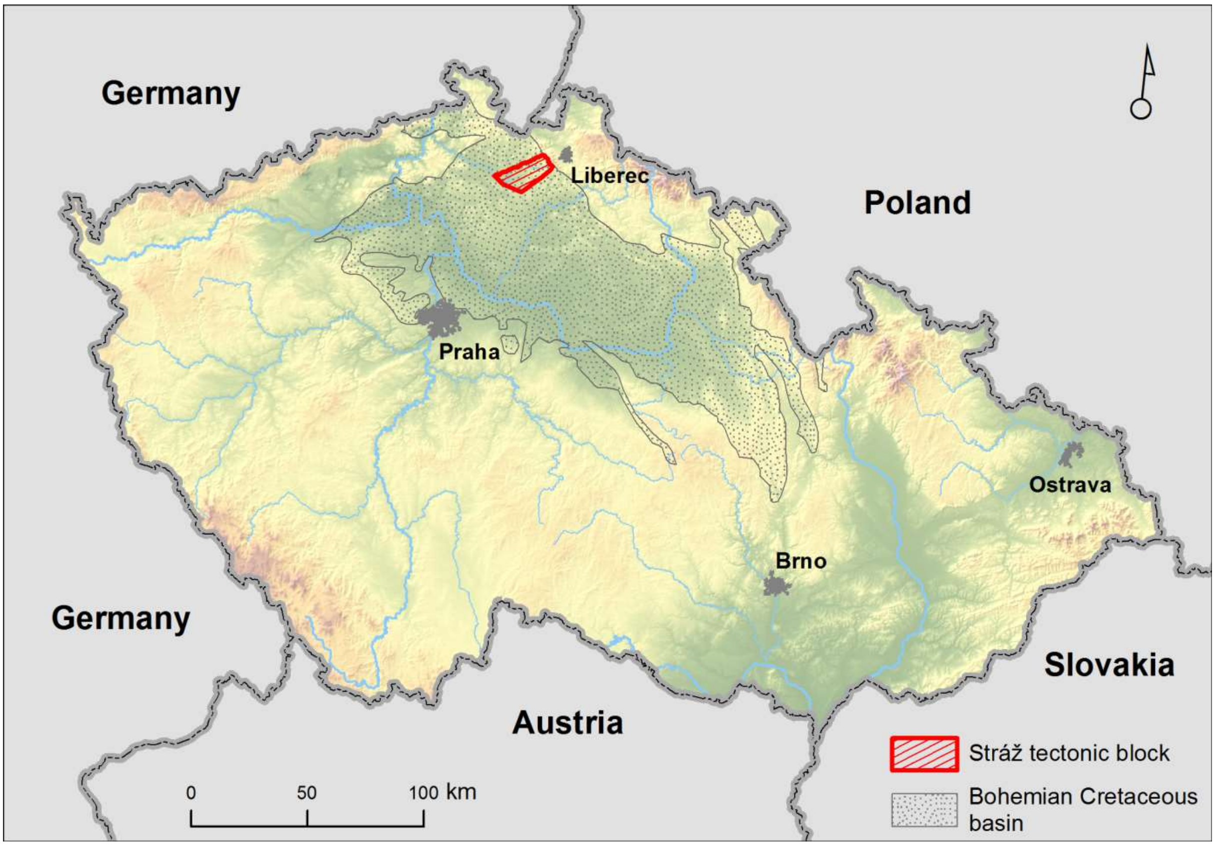

FIG. 1. Position of Straz tectonic block in the Czech Republic courtesy of DIAMO s. e., basemap data: CUZK, VUV T.G.M.).

3. HISTORY OF UNDERGROUND EXPLOITATION

Underground mining started in 1971 when the No. 1–North and nearby No. 2 shafts were sunk near the Hamr na Jezere village. Hoisting shaft No. 3 was sunk and started operation in 1978 and the mining field between shaft No. 1 and shaft No. 3 interconnected. This became the Hamr I Mine complex. Shaft No. 13 of Hamr I Mine was sunk deeper with the expansion of the ventilation and logistics links. Construction of the Hamr II Mine started in 1980 but it was not finished. The smaller, two shaft Krizany Mine was put into operation in 1982. The underground mining technologies used were very progressive for the time. Several variants of the “room and pillar” mining method, with a complete filling of the excavated area with a hydro-congealable backfill, were used. Room ceiling heights ranged from 5 to 13 m with the average width of around 5 m. Mines were successively equipped with complete trackless machinery. The ore was drilled using single-carriage drilling machines. Ore was mucked by conveyor loaders into staple pits in under bed drifts. Excavated rooms were initially shored with timber, then metal support structures were installed with specialized bolting equipment.

Underground mining peaked between in the years between 1983 and 1989, when annual uranium production ranged from 800 to 900 tonnes. Construction of the ore chemical processing plant (mill) started in 1973 on the east side of the Lipka hill. Mill operation started in 1979. Milling technologies are further described in detail in [3]. Ore processing in the mill had following main steps:

- Physical treatment — grinding then sorting the ore into coarse and fine fractions;
- Hydrometallurgical treatment — leaching with a sulphuric acid (H_2SO_4), ion exchange process to strip, precipitate and filter the uranium concentrate (ammonium diuranate), drying, weighing and filling the uranium concentrate into containers;
- After leaching, the exhausted ore was deposited as mud in the nearby tailings pond.

For mining extraction, it was necessary to dry out the Cenomanian reservoir rock. The amount extracted escalated together with the development of the working face and its greatest extent exceeded 35 m^3/min at the Hamr I mine. The Krizany Mine field was situated in a shallow local depression (negative pressure), the base of which is higher than that of the Cretaceous surrounding the Hamr I mine field. As a result, pumping here did not, even at its maximum, exceed 10 m^3/min.

Pumped water was divided into 3 categories and the ratio distribution of each water gradually altered. Clear waters derived from holes bored both from surface and mine works was either neutral or acid. Neutral clear water was decontaminated by means of ion exchangers, acidic mine waters were treated in the neutralization station after separation of dissolved uranium. Treated water was released in to the river Ploucnice, part of the pumped (uncleaned) water was forced into the hydraulic barrier.

Water collected in mine pits was brought up to the top of mine by pumping station. Due to the high content of solids the above-mentioned cleaning technologies could not be applied. They were deactivated through co-precipitation ^{226}Ra in reaction of barium chloride with sulphate ions. Then they were brought into the sedimentation tank to let the sludge settle. Sludge rich in uranium was periodically selected and brought to the chemical treatment plant.

The reduction of uranium mining and milling in the Straz pod Ralskem–Hamr na Jezere region began at the end of the 1980s. Construction of Hamr II Mine–Luzice was stopped and the mine was subsequently closed. The Krizany Mine was also shutdown. The Czech government decided in 1993 to stop mining at Hamr I and the mine was put into a mothball regime.

It was decided to start the disposal of both Hamr I Mine and the chemical processing plant (mill) in 1995.

Over 11600 t of uranium was produced from the deep mining.

4. HISTORY OF IN SITU MINING

Chemical leaching of uranium in the region of Hamr na Jezere–Straz pod Ralskem has been under way since 1967. During this period, there have occurred many changes in the application of this method. This brought about an enormous development of fields and boosted uranium production. The area of exploited areas grew several hectares every year. The number of drilled technological wells (both injection and recovery) used in the ISL process was in the hundreds. The last well field, VP–26, was put into operation in 1993. The total area of well fields reached 6.5 km^2.

ISL technology is divided into several operations:

- Preparation and underground injection of leaching solution into wells;
- Pumping uranium containing solution from underground recovery wells;
- Transporting the leaching solution to injection wells and the recovered solution back to the processing plant;
- Uranium containing solution was treated at chemical plant with an ion exchange process and the effluent reused for preparing additional leaching solution.

The treatment capacity of chemical plants and other technological units was built in parallel to well field development. Recovered solution was treated at chemical plants with classical ion exchange technology:

- Uranium sorption on resin;
- Resin regeneration with nitric acid;
- Uranium concentrate thickening and precipitation with ammonia;
- Filtration and drying.

Ammonium diuranate (the so-called yellow cake) was the final product. The maximum production by ISL extraction was reached in 1976–1977, when uranium production was over 850 t per year.

Unfortunately, this method resulted in detrimental impacts to the environment, mainly the groundwater of the Cenomanian aquifer. As a consequence, the water of the Turonian aquifer being in close vicinity to high quality potable water sources was also jeopardized. For this reason, it has been decided to decommission and remediate the chemical plant. Expansion of the ISL well fields ended in 1991. Operations continued on a limited scale only from 1992 with large decrease in sulphuric acid consumption. Research and development of remediation technologies started at the same time.

The Czech Republic decided to liquidate the ISL Mine in 1996.

5. GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

The deposits in Straz pod Ralskem and Hamr pod Ralskem are part of a tectonic unit known as the Straz block, representing Cretaceous stratifications reaching from the Cenomanian up to the Middle Turonian (Fig. 2). The Straz block extending over an area of 194 km^2 is bounded along its entire periphery by tectonic lines (Luzice fault to the NE, Straz fault to the NW, the Devil's Walls zone of neovolcanites to the SE, and Hradcany fault to the SW, see Fig. 2). At its NW boundary the Straz fault separates the Straz block from another Cretaceous plate, the Tlustec block, featuring a subsidence of as much as 600 m against the Straz block. The over all thickness of the Cretaceous sediments is 140–400 m.

Within the Straz block there are two basic groundwater aquifers with porous or porous–fractured permeability where nearly all groundwater flow and accumulation take place. These aquifers are the Middle Turonian and Cenomanian sandstones. The aquifers are separated by a Lower Turonian formation (siltstones) acting as an aquitard [4].

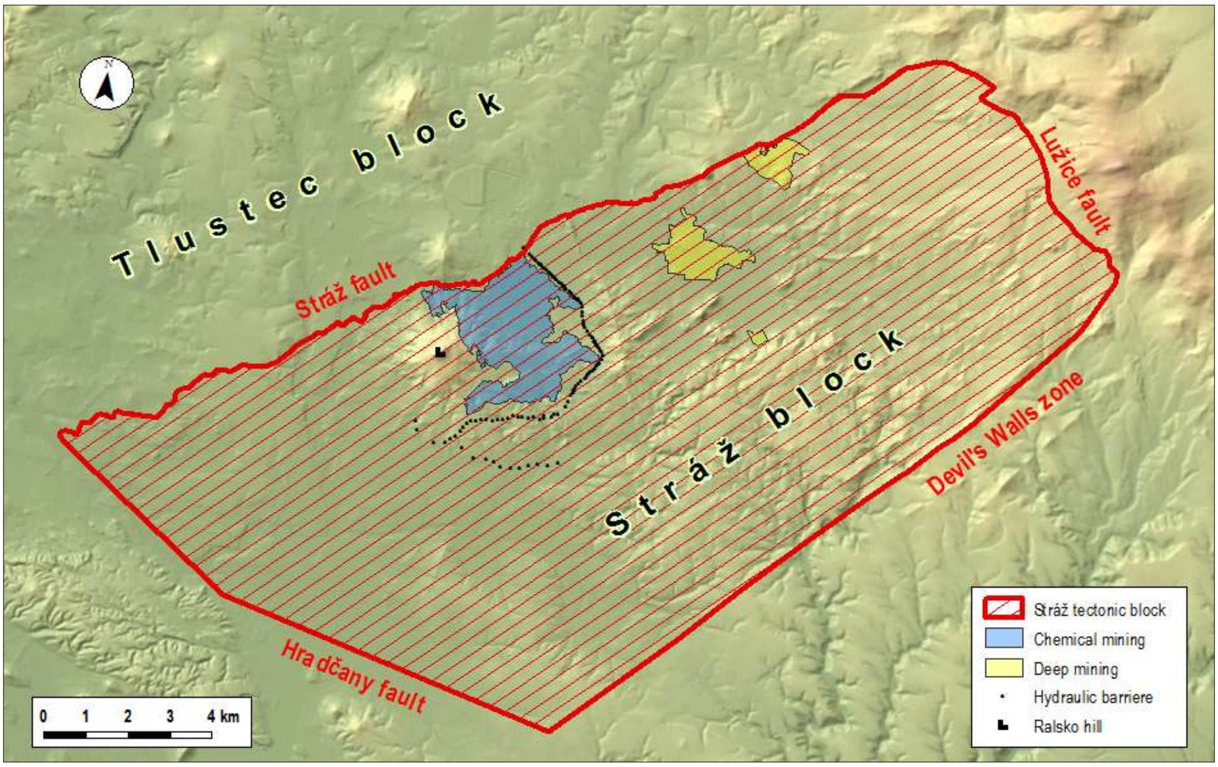

FIG. 2. Situation of the co–existence of the both types of mining (courtesy of DIAMO s. e., basemap data: CUZK).

5.1. The Turonian aquifer

The Turonian aquifer is linked to the Middle Turonian formation represented by sandstones ranging from fine-grained to coarse grained. The thickness of the Turonian aquifer in the Straz block ranges from less than 10 m up to over 150 m with average thickness about 70 m. The Turonian aquifer has an unconfined groundwater level throughout the Straz block area. The aquifer is replenished across the entire area of interest by rainwater recharge. The general groundwater flow within the Turonian aquifer occurs in the direction from NE to SW. The piezometric groundwater level in the Turonian aquifer ranges from 445 m above sea level in the NE part of the Straz block to 265 m above sea level in the SW part of the Straz block. The hydraulic conductivity of the Turonian aquifer is of the order of 10^{-4} to 10^{-5} m/s [4].

5.2. The Cenomanian aquifer

The Cenomanian aquifer is linked to the Cenomanian marine sedimentary formations represented by sandstones. Low permeability sandstones and other sediments of freshwater continental Cenomanian are located in the lower part of cenomanian strata. The thickness of the Cenomanian aquifer is approximately 70 m. The Lower Turonian aquitard, of a thickness of ~60 m acts as an impermeable barrier and separates the Cenomanian and the Turonian aquifer. The recharge area of the Cenomanian aquifer is situated close to the Luzice fault (Fig. 2). The groundwater piezometric level around that location varies from ~305 to 320 m above sea level. The remote Labe River valley constitutes a main drainage area. The Cenomanian aquifer has a confined groundwater level in the area of interest (Fig. 3). Before the uranium mining was launched in the region the natural direction of groundwater flow in the Cenomanian aquifer had been from NE to SW. Currently the dominant direction of groundwater flow is towards the centre of the depression cone being flooded at the Mine Hamr I (Fig. 3). The piezometric groundwater level of the Cenomanian aquifer in the in situ leaching area is influenced by the implementation of remediation technologies. The hydraulic conductivity of the Cenomanian aquifer is of the order of 10^{-5} to 10^{-6} m/s [4].

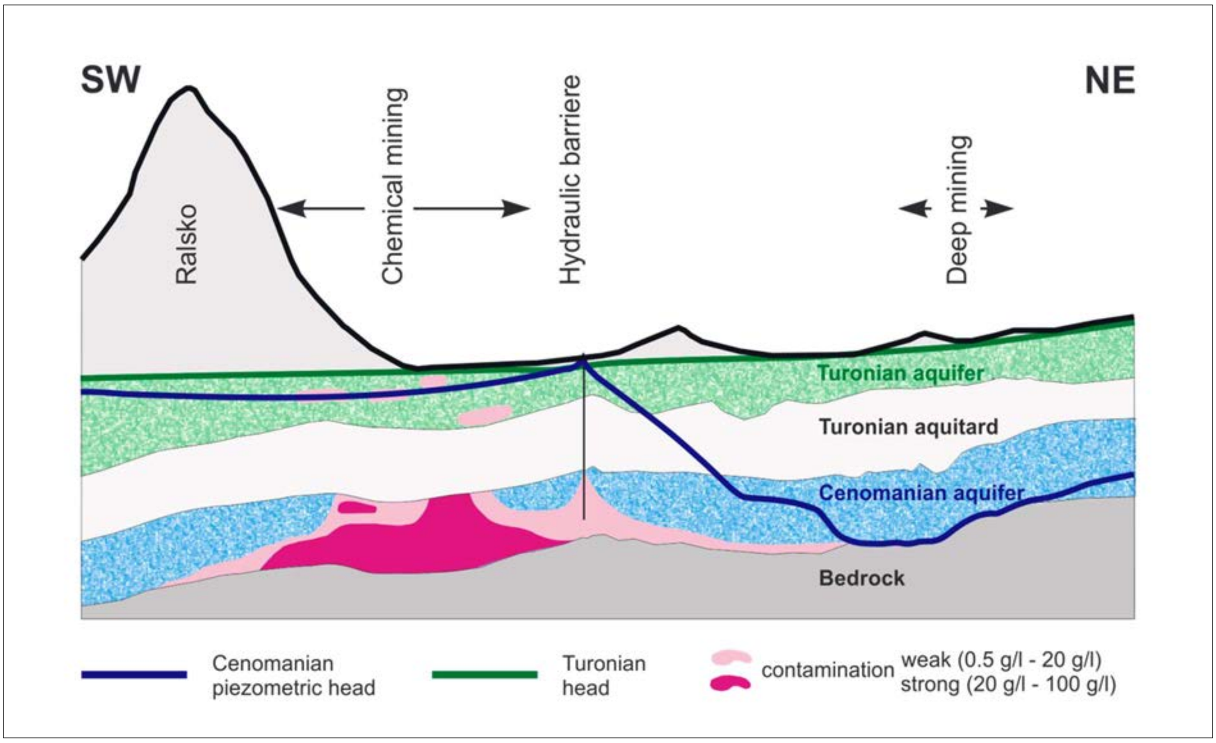

FIG. 3. Schematic cross-section of the area (courtesy of DIAMO s. e.).

6. THE EXTENT OF THE CONTAMINATION

Over the period of chemical leaching of uranium (~32 years), over a million tonnes of sulphuric acid and other chemicals have been injected into the ground. Most of the products (approx. 99.5 %) of the reactions of the acids with the rocks are located in the Cenomanian aquifer. The contamination of Cenomanian aquifer covers the area larger than 24 km^2 (see Fig. 4). The influenced volume of groundwater is more than 380 million m^3 of groundwater. The total amount of dissolved SO_4^{2-} is about 3.6 Mt (6 Mt of total dissolved solids). The extent of contamination in Cenomanian aquifer prior remediation in 1996 is shown in Fig. 4. Approximately 0.5 % of the contamination is located in the Turonian aquifer. The contamination of Turonian aquifer has the character of locally isolated plums. The total amount of dissolved SO_4^{2-} is about 7 900 t (17 000 t of total dissolved solids). The influenced volume of groundwater is 26 700 m^3. The pollution extent in Turonian aquifer in 1996 is shown in Fig. 5.

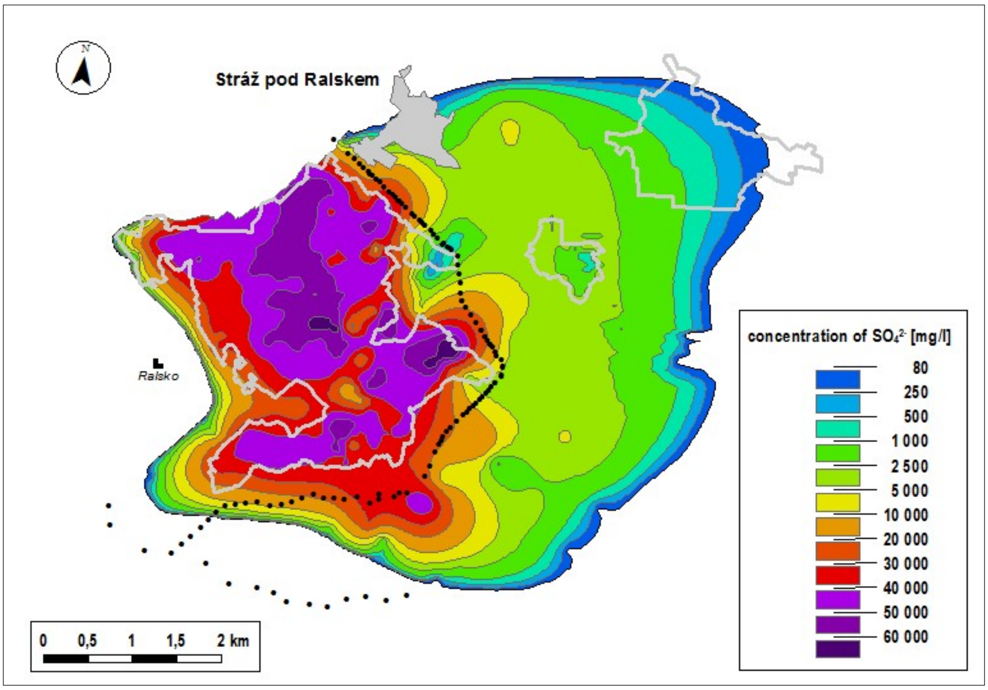

FIG. 4. The contamination extent in Cenomanian prior remediation in 1996 (courtesy of DIAMO s. e.).

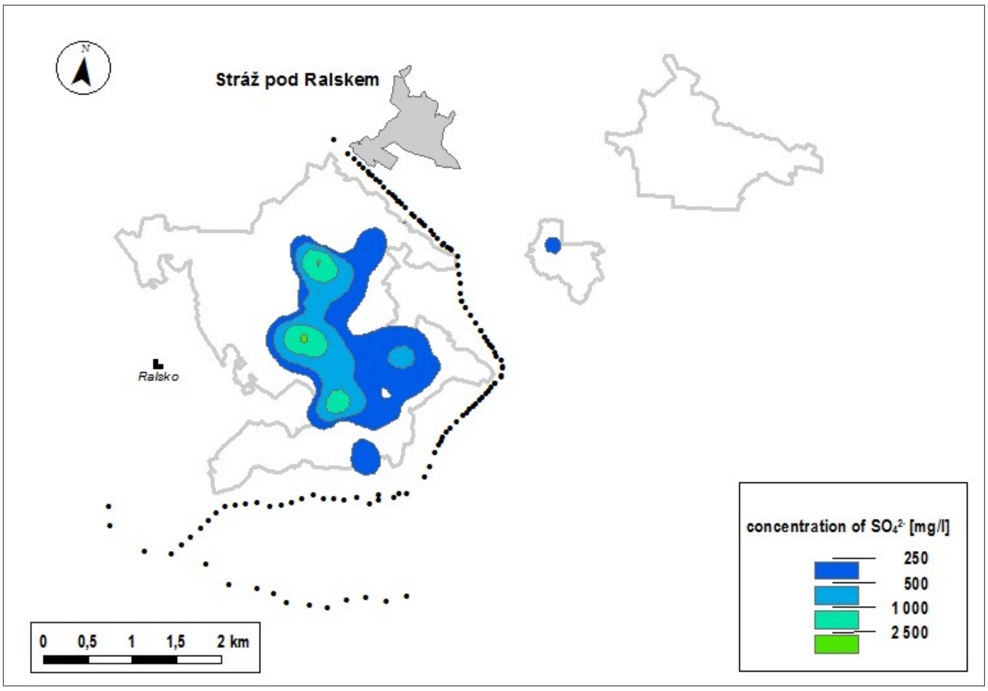

FIG. 5. The contamination extent in Turonian in 1996 (courtesy of DIAMO s. e.).

7. REMEDIATION OF IN SITU LEACHING AREA

The injection of the leaching medium during chemical in situ leaching of uranium directly in the rock environment strongly influences this environment and groundwater. The Turonian aquifer is a very important source of drinking water. The decision to clean this aquifer was already made during ISL mining operations and cleanup started at that time. The final decision about the need to clean the Cenomanian aquifer was adopted in 1992. Operations continued on a limited scale only from 1992 with large decrease in sulphuric acid consumption. Research and development of remediation technologies started at the same time. The Czech government decided to liquidate the ISL Mine in 1996. Realization of the long time period needed for restoration resulted from an analysis of the situation. Remediation will take several decades and will require new investment and significant financial expenses.

The remediation consists in pumping of the contaminated groundwater, removing of the contaminants and treatment of the cleared water. The objectives of the remedial activities are described in following points:

- To restore the rock environment to a condition guaranteeing continuing usability of Turonian water of Northern Bohemian Cretaceous aquifers;
- To decommission bore holes and surface installations;
- To incorporate the surface of leaching fields into the ecosystems taking into account regional systems of ecological stability and urban plans.

7.1. Present state of remediation

In the contrast to older remediation framework described in [1, 2] and [4], the chain of remedial technologies has changed. Currently four main remedial technological installations are used (Fig. 6):

- "Station for acid solutions liquidation" (e.g. evaporator and alum crystallization);
- "Mother liquor reprocessing" station;
- "Neutralization and decontamination station NDS 6";
- "Neutralization and decontamination station NDS 10".

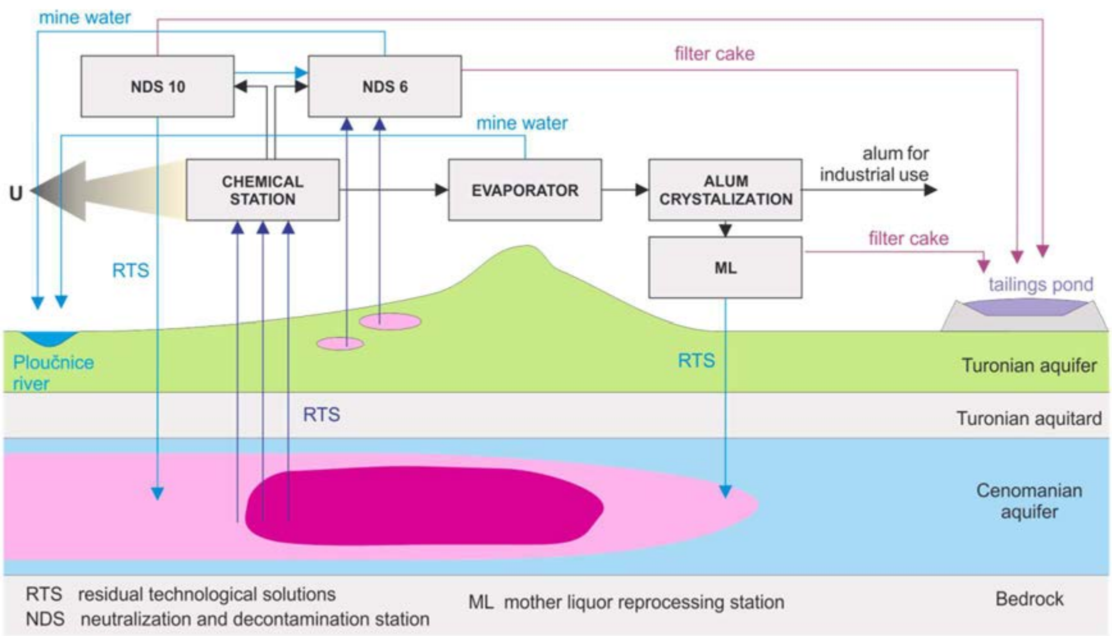

FIG. 6. Scheme of remediation process – technology chain (courtesy of DIAMO s. e.).

Total capacity of this complex should be sufficient to reach the target values of remedial parameters in 2037 according to model calculations. The remediation action consists of: the pumping of residual solution to the surface, the separating uranium from the solution and the reprocessing of the contaminants into commercially usable or ecologically storable products. Approximately 3.6 Mm^3 of water is annually treated and disposed during the remediation of Turonian and Cenomanian aquifers. The annual mass of extracted contaminants in the period 2006–2015 is shown on Fig. 7.

The technological chain of acidic solution remediation begins with the removal of dissolved uranium ions. The 'chemical plant VP–7' is used for stripping uranium from solutions. It was originally used during ISL operations. The principle is the sorption of uranium with the aid of ion exchange, elution with HNO_3 and coagulation with NH_4. The input is max. 4.2 m^3/min of residual technological solutions pumped from the ISL mine. The output is 13 kg U per hour.

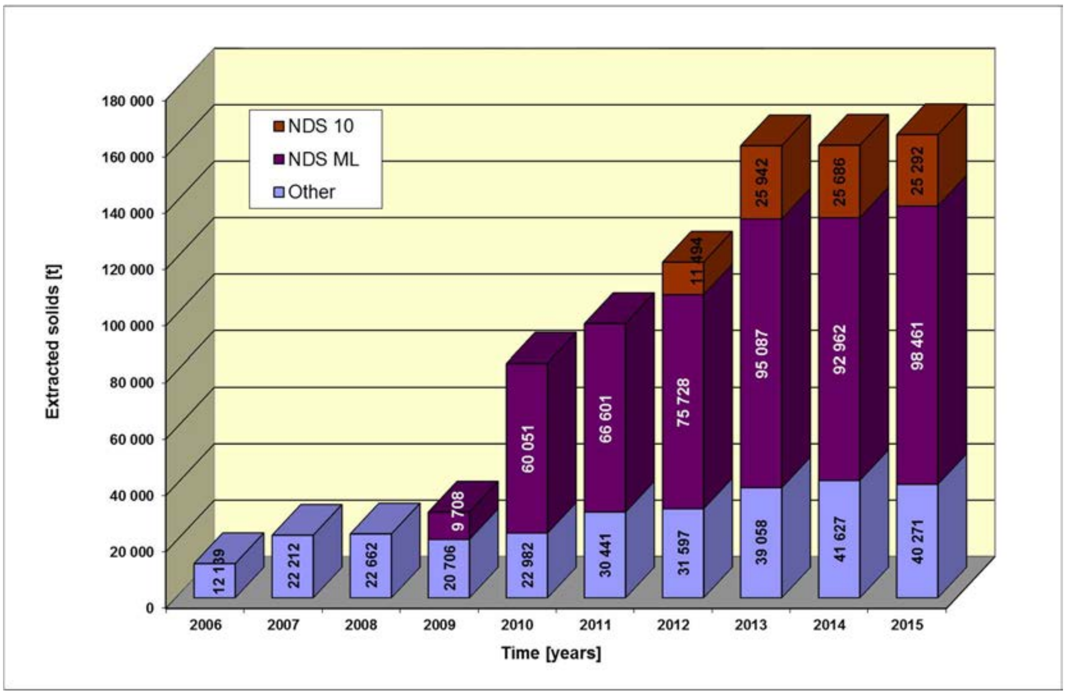

FIG. 7. Annual mass of extracted solids in the remediation process (courtesy of DIAMO s. e.).

7.2. Station for acid solutions liquidation I

The "station for acid solutions liquidation" (SLKR I) was put to operation as the first remediation technology unit in June 1996. Other parts of this technological unit were subsequently put into operation. Simplified technological scheme of the station is shown on Fig. 8. The treatment of residual technological solution used there is thermal thickening (evaporation) in 3 evaporators. Part of SLKR I is the technology for crystallizing ammonium–aluminium–sulphate in 4 crystallizers.

This station input (per 1 evaporator) is a maximum of 2.5 m^3/min of residual technological solution from the 'chemical plant VP–7' with TDS concentration about 60 g/L.

This station outputs are:

— Clean water, of sufficient quality for disposal into the nearby Ploucnice River;
— Crystals of ammonium–aluminium–sulphate, so-called alum;
— Thickened concentrated solution–mother liquor.

7.3. Mother liquor reprocessing station

The mother liquor produced in SLKR I is treated here. The technological principle is precipitation with the use of lime suspension. A wide array of other technological processes is implemented here. The most important constructions are placed at the tailings pond area. Construction started in 2007–2008 and the trial operation started in September of 2009 then since 2010 the station is in full operation. Two-stage neutralization with the aid of the lime milk is the process realized in this station (1^{st} stage to pH 5.5, 2^{nd} stage to pH 11). Basic details are given in Table 1 and a photograph of the filter presses of the plant in Fig. 9.

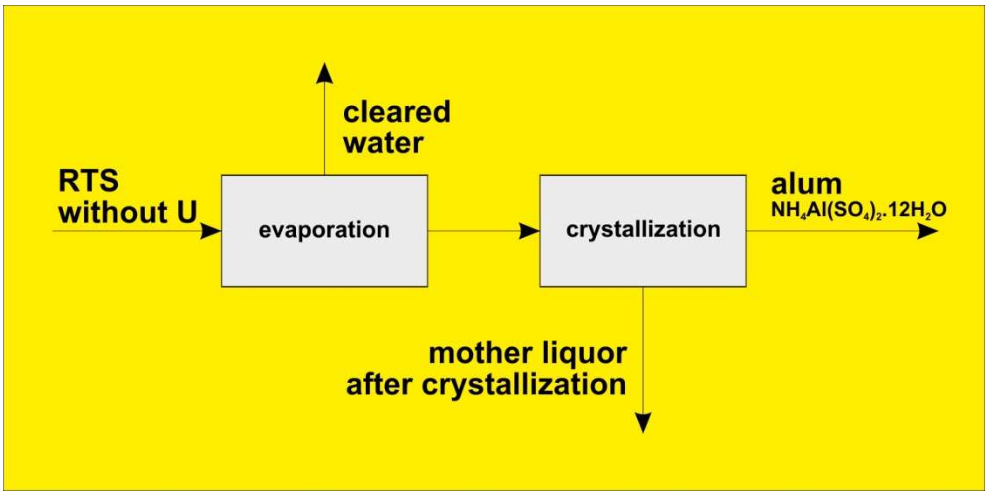

FIG. 8. Scheme of SLKR I (courtesy of DIAMO s. e.).

TABLE 1. BASIC DATA FOR SLKR I

Input:	2.2 m^3/min of dilute mother liquor with TDS concentration 120 g/L.
Output:	up to 200 000 m^3 of filter cake to tailings pond yearly.
Cleared water:	injected into mine Hamr I.
Ammonia water 25%:	partially reused in SLKR I, overbalance sold in the market.

FIG. 9. Filter press — NDS ML (courtesy of DIAMO s. e.).

7.4. Neutralization and decontamination station NDS 6

Originally this station was used for treating acidic mine water pumped from Hamr I Mine, later it treated contaminated water from Turonian aquifer. Its reconstruction was realized in 2005. Picture of the sedimentation tank at NDS 6 is shown in Fig. 10. Up to 5 m^3 per minute of residual solutions can be treated there. The neutralization technology principle is the reaction between acidic solutions and lime suspension. The forming precipitate is thickened, filtrated and deposited at a tailings pond. Cleaned water is disposed to the river, or injected to marginal parts of the ISL wellfield area (Table 2).

FIG. 10. Neutralization and decontamination station NDS 6 (courtesy of DIAMO s. e.).

TABLE 2. BASIC DATA FOR NDS 6

Input	Max. 5.5 m^3/min of Turonian water, water from tailings pond and weak solutions from chemical plants with concentration about 10–11 g/L of TDS.
Output	Up to 70 000 m^3 of filter cake to tailings pond yearly, water after chlorination discharged into Ploučnice River.

7.5. Neutralization and decontamination station NDS 10

The liquidation of the residual technological solution (RTS) with the concentration of total dissolved solids (TDS) up to 25 g/L by the help of the technology NDS 10 started since 2012 (analogous method like the technology of the mother liquor processing). Simple technological scheme is presented in Fig. 11. The dissolved ammonia is stripped from the filtrate by water vapour. The filter cake is deposited on the tailings pond Straz (Fig. 12). Cleaned filtrate is injected back to the Cenomanian aquifer or discharged into the river. It is supposed to process totally up to 4.4 m^3/min residual technological solution after stepwise launching of two neutralization lines and production of the filter cake up to 80 000 m^3 per year. Filter cake is deposited in the tailings pond, as shown in Fig. 12.

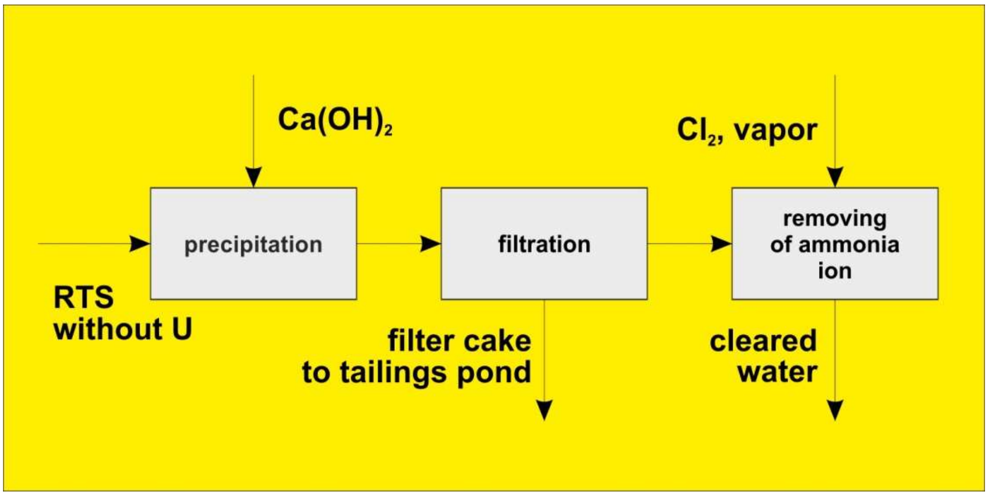

FIG. 11. General scheme of neutralization process (courtesy of DIAMO s. e.).

FIG. 12. Filter cake deposition at tailings pond (courtesy of DIAMO s. e.).

7.6. Target values of remediation parameters

The risks related to the aquifer contamination were formerly presented for instance in [5]. Definite target values of remediation parameters were specified in Risk Analysis updated in 2010 [6]. During processing of Risk Analysis many parameter simulations of long term transport of contaminants with geochemical interactions and intercollector transfer were performed. The limits are based both on median (middle value) and maximal acceptable value of the selected contaminants. These limits should have guarantee that the drinking water sources will never be influenced by contamination in both near and far future. The target values (limits) of remediation parameters are stated in Table 3.

For calculation of median (middle value), the results of hydrochemistry analyses of RTS samples from monitoring well network are used. The maximal acceptable values of parameters concentration are determined from results of logging measurements.

TABLE 3. APPROVED DEFINITION OF THE TARGET VALUES (LIMITS) OF REMEDIATION PARAMETERS [6]

Parameter	Median of concentration (mg/L)	Maximal acceptable value of concentration (mg/L)
Al	800	2400
Fe	150	600
NH_3^+	80	210
SO_4^{2-}	6000	18000
TDS (total dissolved solids)	7000	21000

8. PERSPECTIVE OF REMEDIATION

Within the frame of research and development works the model variant computations are made to choose the optimal remediation process. Preparing of the remediation technologies, immobilization of the contaminants in situ, verification of the situation in the rock environment (possibility of Cenomanian–Turonian overflow) and evaluation of the influence of the contamination in the fucoid sandstones on the remediation objective parameters setting have already been solved during the research and development works. The remediation scenario, which will ensure termination of the remediation since the year 2037 while new limits are proposed, is continuously adjusted on the basis of the model computations. The results of remediation scenario calculation are shown in Fig. 13.

It is expected that the concentration of the contaminants in RTS in the area of leaching fields will significantly decrease in time. This decrease will influence operating time of SLKR I.

In years 2017 or 2018, the second line of the technology NDS 10 will come into operation and the whole capacity of this technology will increase to 4.4 m^3/min. The production of alum will be finished at the end of 2020. Further operation of SLKR I will depend on the chemical composition and concentration of the residual technological solutions. NDS ML will treat 3 m^3/min of RTS, whose composition will be dependent on the SLKR I operating regime. The operation of the technology SLKR I will be terminated after decrement of the concentration in the pumped residual technological solutions. Henceforth the RTS will be directly pumped to neutralization in the technologies NDS ML and NDS 10.

Then the liquidation of wells, surface objects and technical and biological recultivation of all areas influenced by uranium mining in Straz pod Ralskem will begin. The post remediation monitoring at the residual well net DIAMO (or wells CHMI) will follow.

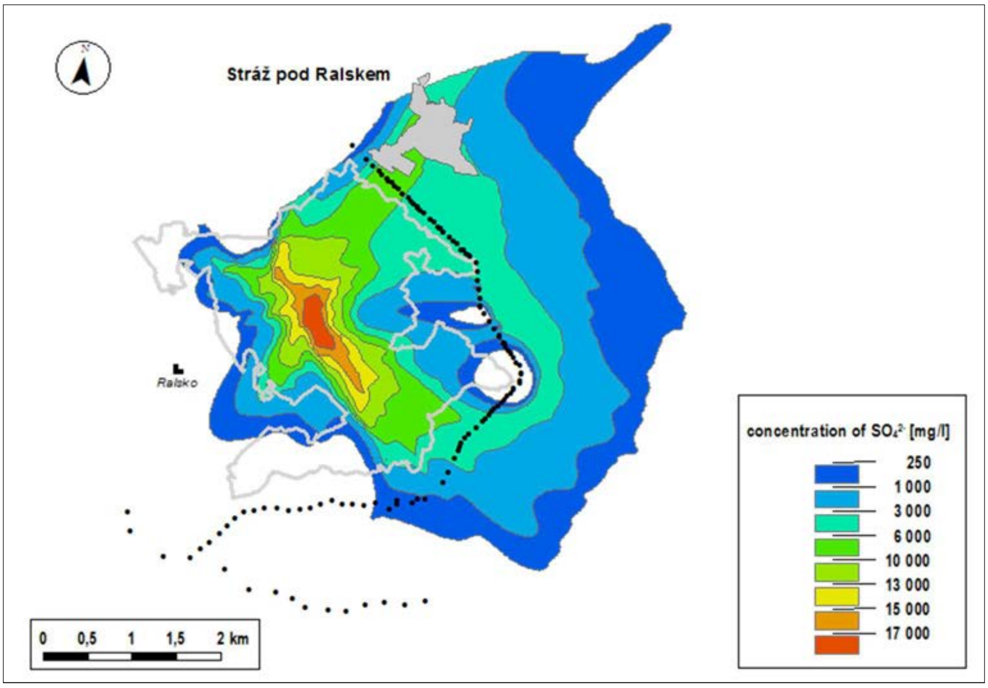

FIG. 13. Numerical model prediction of contamination extent after remediation in 2037 (courtesy of DIAMO s. e.).

9. CONCLUSIONS

Uranium deposits in the Straz block were mined in two mining methods – standard mining and chemical mining. The close coexistence of these mining methods forced a number of interventions to hydraulic regimes in the area. Their subsidiary and unadvisable result is a large-scale contamination of underground water.

The contamination of rock environment caused by chemical mining potentially endangers groundwater and surface water sources of drinking water in the region. If Cenomanian groundwater level reaches its original level, there will be a risk that solutions will pass through the lower Turonian insulator due to the head difference in some areas. This insulator is weakened by tectonic activity as well as by passages of several thousands of bores into the Turonian reservoir rock. The danger is not acute, it would be theoretically relevant in tens or hundreds of years. The drinking water sources could, however, be adversely affected for centuries if the pollution was not treated properly.

The remediation process is financially, technically and organizationally complicated. Due to extremely concentrated solutions in Cenomanian aquifer (up to 100 g/L of dissolved substances) and very low pH (< 1), no standard cleaning technology is suitable. The remediation requires suitable technological equipment and gradual pumping and treatment of the solutions by a variety of methods. According to the model prediction the remediation will take at least 30 years and the costs are expected in the amount of EUR 1.5 billion.

ACKNOWLEDGEMENTS

Special thanks to E. Piskova for great help with picture creation and graphical editing.

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STATUS OF THE MOAB UMTRA PROJECT LONG TERM REMEDIAL ACTION[25]

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Abstract

The U.S. Department of Energy (DOE) has managed the Moab Uranium Mill Tailings Remedial Action Project in South–Eastern Utah since 2001. Systems were designed and constructed in 2008 and 2009 for moving the 14 Mt of uranium mill tailings away from the Colorado River and permanently storing them in a disposal cell being constructed 48 km north near Crescent Junction, Utah. From design and infrastructure construction through the operational phase of the project, the highest priority has continued to be placed on workplace safety. Based on the approved lifecycle estimate, the project is ahead of the schedule and below the cost at completion.

1. BACKGROUND

The Moab uranium ore processing facility was constructed about 5 km northwest of the city of Moab in South-Eastern Utah (Fig. 1), and operated from 1956 to 1984. Mill tailings, what remained after the ore was processed, were slurried to an unlined impoundment in the western portion of the site. When processing operations ceased, the uranium mill tailings and other contaminated materials, collectively known as residual radioactive material (RRM), totaled an estimated 14 Mt (9.2 Mm^3) and covered 53 ha.

Debris, including asbestos, from dismantled mill buildings and associated structures was buried in the southern corner of the pile and an interim cover was placed over the pile as part of decommissioning activities.

Through Congressional legislation, ownership of the site was transferred to DOE in 2001. DOE issued a Record of Decision [1] in 2005 to document its decision to relocate the RRM to a DOE-constructed disposal cell 48 km north near Crescent Junction, Utah, using primarily rail transportation. DOE manages the cleanup of the former millsite under the Moab Uranium Mill Tailings Remedial Action (UMTRA) Project. In addition, the scope includes remediation of properties near the millsite, called vicinity properties that exceed cleanup standards. Because the Moab millsite was never abandoned, allowing public access to the tailings, there have not been many vicinity properties requiring cleanup.

Material in the tailings pile ranges from outer compacted, coarse sands to inner fine clays. Especially in the center of the pile, the tailings have high water content. Excess water in the pile drained into underlying soils, contaminating the groundwater, which discharges to the Colorado River. The two main contaminants in groundwater are ammonia and uranium. Active remediation of the contaminated groundwater is included in the project scope.

[25] Paper first presented at the Technical Meeting of the UMREG in Dolni Rozinka, Czech Republic, September 2013, by P. Waggitt on behalf of D. Metzler (updated in 2016). Copyright U.S. Department of Energy, published with permission.

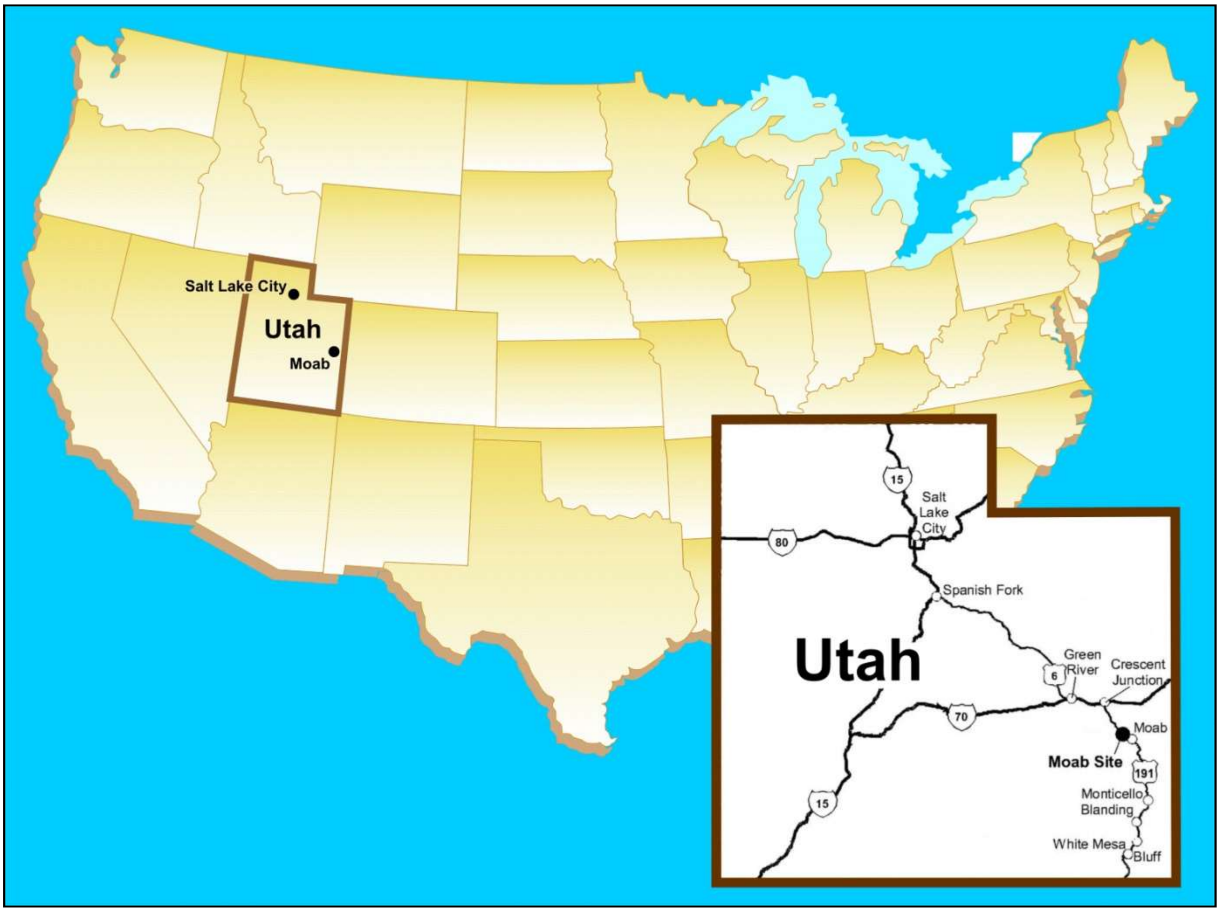

FIG. 1. Location of Moab site.

2. STATUS OF RRM SHIPPING AND DISPOSAL

The project has periodically obtained aerial photographs and topographic contours to confirm the estimated 14 Mt in the tailings pile has not changed. Figure 2 shows the Moab site in 2000 and Fig. 3 is a similar view of the site taken in 2014.

The geological isolation of the Crescent Junction site made it an ideal choice for off-site disposal of the RRM. The project prepared a Remedial Action Plan [2] that documents the basis for constructing the disposal cell near Crescent Junction. In 2008, the U.S. Nuclear Regulatory Commission (NRC) gave its conditional concurrence on the plan.

Also in 2008, infrastructure construction began at the Moab and Crescent Junction sites, including RRM handling and removal systems. The project began RRM shipments in April 2009 and reached the halfway mark of 7 Mt in late January 2016. The project currently ships one train a day, four days per week.

Excavation of the disposal cell is being performed in phases with the first two phases completed. The final cell will occupy roughly 100 ha. Cell excavation extends 7.5 m below grade into weathered Mancos Shale. RRM is placed in the unlined cell to 7.5 m above grade.

FIG. 2. Moab site, 2000.

FIG. 3. Moab site, 2014.

The 3-m-thick final cover on the disposal cell consists of multiple layers of soil and rock. Interim cover has been placed on portions of the cell that have met the final grade for RRM. Final cover layers have been installed over portions of the interim cover. The basalt rock used for the biointrusion layer and the uppermost layer is being quarried to meet NRC specifications for durability, and is being hauled from 130 km away. The interim cover, radon barrier and the frost protection layer come from material excavated on site at Crescent Junction. Excess material from the cell excavation is used to form a protective barrier from runoff on the upslope side of the disposal cell. Figure 4 shows the extent of disposal cell construction as of April 2014.

FIG. 4. Crescent Junction disposal site, 2014. From left, final cover (dark grey), interim cover placed (light tan), RRM being placed (red), and excavated cell unfilled.

3. GROUNDWATER CLEANUP STATUS

As an interim groundwater remedial action, the Moab Project installed a series of wells in 2003 along the Colorado River to capture contaminant mass before it reaches the river. The interim action system was expanded several times and extraction wells were added closer to the tailings pile, the source, to optimize contaminant mass removal. Figure 5 shows the volume of extracted water and ammonia and uranium mass removed between 2003 and 2015. As indicated in the figure, although the volume of groundwater extracted has significantly decreased since 2009 when the extraction wells were added closer to the pile, the mass removal has remained fairly constant because of the optimization.

Extracted water was pumped to a lined evaporation pond or sprayed through evaporative units on top of the tailings pile. Extraction was suspended in fall 2015 to prepare for emptying the pond before its removal in spring 2016. When extraction resumes, the water will be pumped directly to a storage tank for use as dust control on the pile.

The wells closest to the river were converted to injection wells so that freshwater could be injected to create a hydraulic barrier that reduces discharge of contaminated water to habitat areas where endangered fish species may exist during the summer months. In addition, freshwater can be diverted to side channels of the river to further reduce ammonia concentrations.

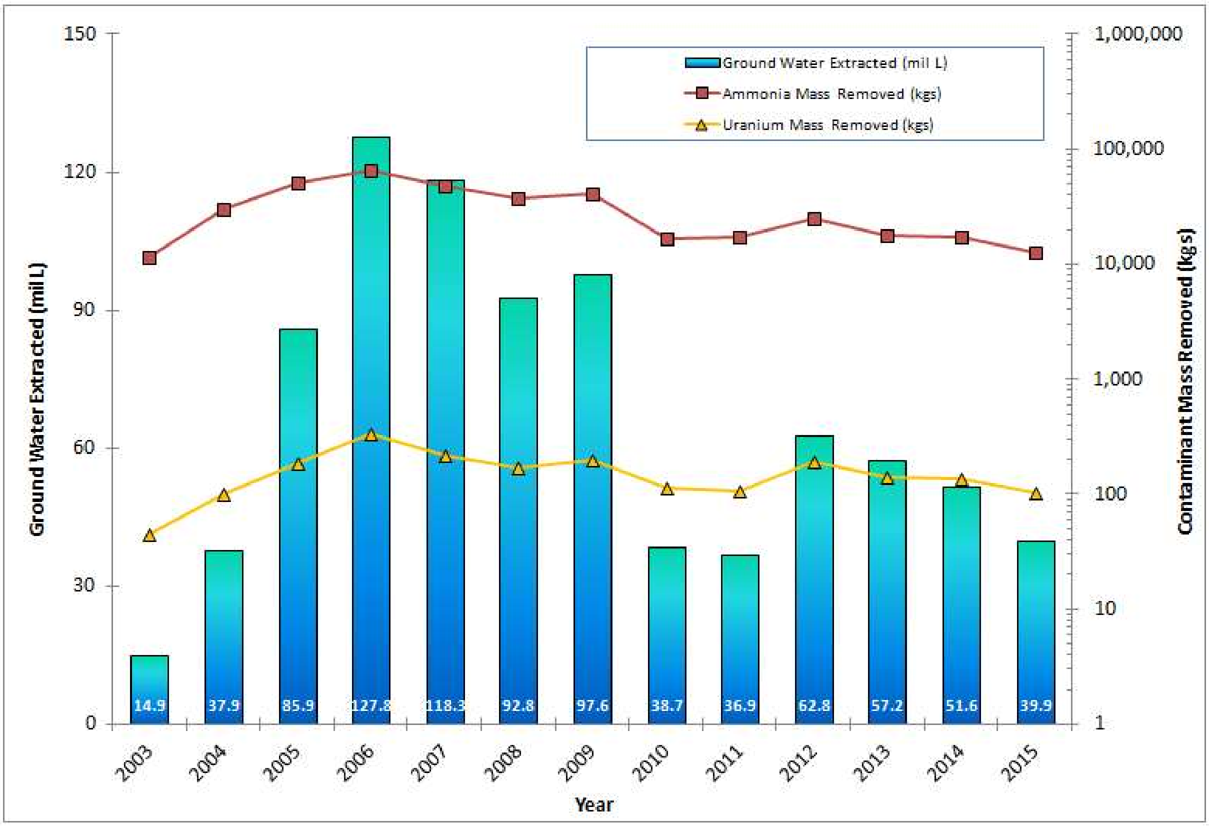

FIG. 5. Volume of groundwater extracted and ammonia and uranium mass removal, 2003–2015.

Performance of the groundwater interim action is assessed through semi-annual sampling of surface water locations, extraction/injection wells, and monitoring wells. Through September 2015, more than 863 ML of contaminated groundwater had been extracted, including 390 000 kg of ammonia and 2040 kg of uranium.

4. THE IMPORTANCE OF SAFETY

Since the beginning of the Moab Project, DOE has placed an emphasis on safety and worked to develop a positive safety culture [3]. The project holds safety luncheons at the work sites that include presentation of awards to employees who exhibit a positive safety attitude, and an Employee Safety Committee was formed that consists of non-management workers from across the disciplines. The project suffered a setback in its safety culture prompted by a big influx of employees hired with funding from the American Recovery and Reinvestment Act of 2009

(Recovery Act). Many of the additional workers came from industries that did not embrace a strong safety culture.

DOE has renewed its emphasis on safety through the development of a Safety Conscious Work Environment, or SCWE, across its complex of sites. SCWE stresses the importance of fostering work environments in which employees can raise safety concerns to management without fear of retribution. A strong SCWE involves increasing management time spent in the field and frequent engagement with employees; credibility, trust and reporting errors and problems; open communication and creating an environment free from retaliation; and encouraging a questioning attitude.

The Moab Project has made efforts to enhance its SCWE by soliciting worker comments through employee safety questionnaires; using the Safety Committee to provide feedback to management; safety walkdowns by management; encouraging reporting of concerns through implementation of an Employee Concerns Program; and rejuevnating the Safety Incentive Program. Posters at the worksites and discussions at daily safety meetings promote SCWE awareness.

DOE sets higher standards than comparable private industries for safety indices. At the end of December 2015, the project had reached 2.5 million work hours without a lost-time injury or illness.

5. COST AND SCHEDULE

The Moab Project received approval of its lifecycle baseline in 2008 at an estimated cost of US $1 billion, with a project completion date of 2028. As the Project has progressed, and with funding received through the Recovery Act, the lifecycle estimate has dropped to US $900 million with a 2025 completion date.

6. FURTHER CHALLENGES

Current and anticipated project funding supports moving 540 000 to 590 000 tons each fiscal year. Along with excavating, transporting and disposing of RRM, the project must conduct other activities, such as equipment maintenance, excavate the remainder of the disposal cell, and place interim and final cover. Combating complacency and developing a SCWE will be challenges as project activities become routine. Despite these challenges, the project will strive to be completed on schedule and within budget.

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THE ROLE OF MINERALOGY IN PROCESS ENGINEERING[26]

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Abstract

There are many different types of uranium minerals and their processing routes are often dictated by the types of uranium and gangue minerals in the ore. Mineralogy provides the insights into chemical as well as physical requirements to process the ore. Mineralogy enables the degree of liberation and the grain size of the uranium and the gangue minerals to be determined. This will provide insight into the comminution circuit required to present the liberated ore to the leach. Mineralogy is an essential input into the mass balance design basis. The paper examines the role of mineralogy in process engineering and demonstrates its application through a case study.

1. INTRODUCTION

Mineralogy is the study of the distribution, identification and properties of the minerals. There are many different types of uranium minerals and associated gangue minerals, making it important to study the mineralogy of uranium ores to provide a guide for the processing of the ore.

Quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) has been used extensively to provide mineralogical data, including:

- Uranium mineral identification and associated probable physical characteristics;
- Identification of the uranium and gangue mineral liberation sizes;
- Major associated gangue minerals;
- Minor minerals of special interest;
- General physical relationship between the various minerals.

There are two primary lixiviant types for recovering uranium from ore: sulphuric acid and sodium carbonate/bicarbonate. The selection of the leach regime is influenced by uranium and gangue mineralogy. Alkaline processes are more suited to secondary uranium minerals whereas the acid processes are employed predominantly to process primary uranium minerals.

The acid leach process has faster kinetics with higher recovery. Compared to the alkaline process, lower temperatures are normally employed in acid leach. Acid leach processes are employed in ores that have preg[27] robbing features. The alkali leach is more selective in terms of impurities elements co-extraction compared to acid leach and often reduces the impurity load that has to be removed in the downstream processes [1].

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[26] Presented at the Technical Meeting on Uranium Production Cycle Pre-Feasibility and Feasibility Assessment, 7–10 October 2013, Vienna, Austria.

[27] Short for 'pregnant solution' a standard term within the industry to indicate a solution with a high concentration of the target element or compound.

2. URANIUM MINERALOGY

2.1. Primary minerals

Uranium minerals may be termed primary or secondary, depending upon their degree of oxidation and origin. Primary minerals refer to uranium minerals that are formed first and generally have a 4+ valency. The most common forms of primary uranium minerals are uraninite and coffinite (a silicate). Primary minerals other than uraninite and coffinite are a group containing niobium, tantalum and titanium, which are known as multiple oxides of uranium. The group includes the uranium minerals, davidite and brannerite [2]. The composition of some of the common primary uranium minerals are as shown in Table 1.

TABLE 1. COMMON PRIMARY URANIUM MINERALS COMPOSITION

Type	Name	Composition
Oxides	Uraninite / Pitchblende	UO_2
Silicates	Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
	Uranothorite	$UThSiO_4$
Nb–Ta–Ti Complex Oxides	Brannerite	$(U,Ca,Ce)(Ti,Fe)_2O_6$
	Davidite	$(La,Ce,Ca)(Y,U)(Ti,Fe^{+3})_{20}O_{38}$
	Betafite	$(Ca,U)_2(Nb,Ti)_2O_6OH$

2.2. Secondary minerals

Secondary uranium minerals generally incorporate uranium in the 6+ valency and the composition of some of the common secondary uranium minerals are shown in Table 2. The secondary uranium minerals are generally surficial and frequently are found as crusts, powdery aggregates and platy, acicular, fan-like coatings and films [2].

2.3. Liberation

For the leaching process to be efficient, whether it is acid or alkali, the uranium minerals need to be exposed to the leach liquor. Mineralogy is employed to determine the degree of liberation of the value minerals and the gangue minerals. Figure 1 shows an example of uranium minerals in association with chlorite particle using QEMSCAN.

The comminution circuit can be quantified once the grain size and the degree of liberation of the uranium minerals can be determined. Similarly, if at the same time the grain size and the liberation of the gangue from the value minerals can be determined, then beneficiation as an upgrade of the uranium over the gangue can be determined.

TABLE 2. COMMON SECONDARY URANIUM MINERALS COMPOSITION

Types	Name	Composition
Silicates	Sklodowskite	$(H_3O_2)Mg(UO_2)_2(SiO_4)_2.2H_2O$
	Uranophane	$Ca(UO)_2Si_2O_7.6H_2O$
	Uraniferous Zircon	$Ca(UO)_2Si_2O_7.6H_2O$
Phosphates	Autunite	$Ca(UO_2)_2(PO_4)_2.10–12(H_2O)$
	Torbenite	$Ca(UO_2)_2(PO_4)_2.10–12(H_2O)$
	Saleeite	$Mg(UO_2)_2(PO_4)_2.12H_2O$
Vanadates	Carnotite	$K_2(UO_2)_2(VO_4)_2.1–3(H_2O)$
	Tyuyamunite	$Ca(UO_2)_2(VO_4)_2.8H_2O$
Arsenates	Zeunarite	$Cu(UO_2)_2(AsO_4)_2.10–12H_2O$
Carbonates	Schroeckingerite	$NaCa_3(UO)_2(CO_3)_3(SO_4)F.10H_2O$

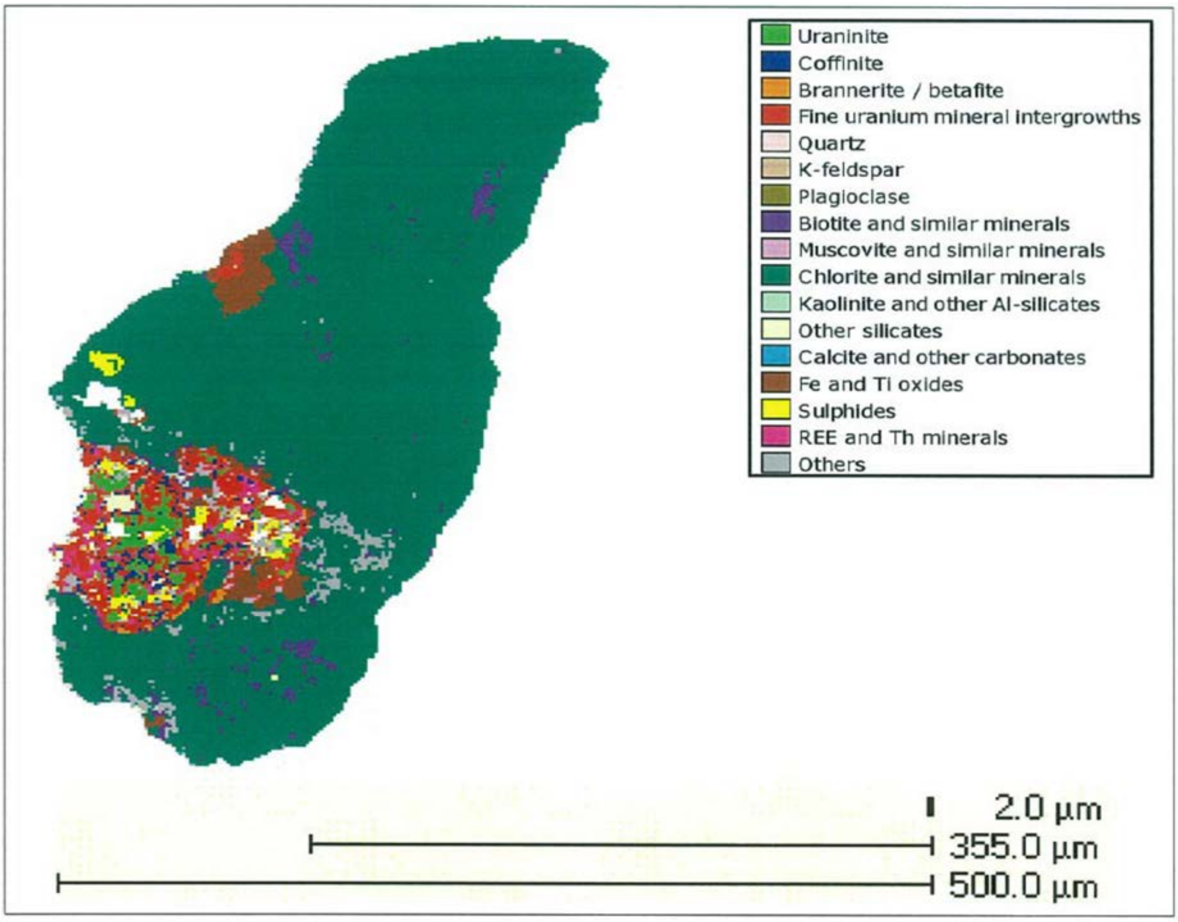

FIG. 1. Mineralogy with grain size measurement.

Beneficiation testwork will need to be performed to confirm the upgrade and recovery from beneficiation methods. Examples of beneficiation methods that have been employed on uranium ore include scrubbing, flotation and gravity method such as up-current classification.

3. GANGUE MINERALS

In the uranium leach processes employing sulphuric acid as the lixiviant, only a relatively small quantity of acid is normally gainfully employed in extracting uranium from the host ore. The remainder of the acid is consumed by the gangue constituent elements [3]. The type of gangue minerals present in the ore can affect the processing route selected. While the uranium minerals may be amenable to both acid and alkali leaching, the process route chosen is influenced by the process economics. Apart from consuming the lixiviant, leached gangue minerals can have detrimental effects on the downstream process.

The effect of the common gangue minerals associated with the uranium minerals and its impact on uranium extraction and recovery processes are examined in this section. The common gangue minerals associated with uranium minerals are as follows:

- Carbonate;
- Sulphide;
- Calcium sulphate/strontium sulphate;
- Fluoride/chloride;
- Phosphate;
- Carbonaceous;
- Rare earth element;
- Soluble silica;
- Clays.

3.1. Carbonate

The presence of carbonate gangue with the uranium minerals may increase the acid consumption rates in acid leaching making this process route uneconomical. Lodeve deposit in France is an example of a deposit rich in carbonates (dolomite, ankerite) [2]. The reaction of carbonate in sulphuric acid leach is represented by Eq.1 below.

$$CaMg(CO_3)_2\,(s) + 2H_2SO_4\,(aq) \rightarrow CaSO_4\,(aq) + MgSO_4\,(aq) + 2CO_2\,(g) + 2H_2O\,(\ell) \qquad (1)$$

3.2. Sulphides

The presence of base metal sulphides gangue with the uranium minerals can make extraction more difficult and may require more aggressive conditions. These sulphides gangue may also increase the oxidant consumption rates. Sulphides may also react with carbonate in alkali leach making this process route uneconomical [4]. Key Lake Uranium in Saskatchewan is an example of uranium orebody with sulphides, such as millerite (NiS) employing acid leaching process [2]. The reaction of millerite with oxygen as oxidant is represented by the Eq. 2 below.

$$NiS\,(s) + 2O_2\,(g) \rightarrow NiSO_4\,(aq) \qquad (2)$$

3.3. Calcium sulphate/strontium sulphate

Gangue minerals with calcium sulphate and strontium sulphate can react with the alkaline reagent in alkali leach process resulting in high reagent consumption rates [2]. The reaction of calcium sulphate with sodium carbonate is represented by the Eq. 3 below.

$$CaSO_4\,(s) + Na_2CO_3\,(aq) \rightarrow Na_2SO_4\,(aq) + CaCO_3\,(aq) \quad (3)$$

3.4. Fluoride/chloride

The presence of halides such as fluoride and chloride in gangue minerals such as apatite can have deleterious effect in the downstream solvent extraction and ion exchange recovery processes.

Apatite is soluble in acid and alkali leach [2]. The reaction of apatite with sulphuric acid is shown in Eq. 4.

$$3Ca_5(PO_4)_3Cl(s) + 3H_2SO_4(aq) \rightarrow 4Ca_3(PO_4)_2(s) + 3CaSO_4(aq) + 3HCl(aq) + H_3PO_4(aq) \quad (4)$$

These halides can compete with uranium ions in downstream recovery processes, loading on to extractant and ion exchange resin as shown in the Eqs 5 and 6 below.

$$2HCl\,(aq) + (R_3NH)_2SO_4(o) \rightarrow 2R_3NHCl(o) + H_2SO_4(aq)\ \text{(solvent extraction)} \quad (5)$$

$$4HCl\,(aq) + ResN_4(SO4)_2(r) \rightarrow ResN_4Cl_4(r) + 2H_2SO_4(aq)\ \text{(ion exchange)} \quad (6)$$

3.5. Phosphate

Apatite leaching will also form phosphoric acid which can further react with ferric in the leach solution to precipitate as ferric phosphate as shown in Eq. 7. This precipitation reaction will deprive the leach of valuable ferric oxidant and kinetically impair the uranium extraction process [3].

$$Fe_2(SO_4)_3\,(aq) + 2H_3PO_4\,(aq) \rightarrow 2FePO_4\,(s) + 3H_2SO_4\,(aq) \quad (7)$$

3.6. Carbonaceous (preg-robbing)

Examples of low concentrations of uranium in black shale deposit include Kolm in Sweden, the Chattanooga shale in the USA, Chanziping deposit in China [2] and the southern Africa carbonaceous deposit. The presence of carbonaceous minerals can hinder uranium leaching [4] and may have preg-robbing effect on uranium extraction.

3.7. Rare earth minerals

Yttrium and the heavy rare earth elements often co-exist with coffinite and to a lesser extent uraninite and brannerite. Rare earth minerals such as synchisite (a fluorocarbonate containing calcium) and churchite (a yttrium phosphate) can dissolve in relatively mild acid leach condition (at pH 1.5) while other rare earth minerals such as monazite, xenotime, bastnaesite and florencite are relatively insoluble at pH above 1 at 55˚C [2]. Rare earth elements can potentially be recovered as a by-product to uranium. An example of uranium deposit containing rare earth minerals is Nolans deposit in Australia [5].

3.8. Soluble silica

Clinochlore, a gangue mineral, can leach in acid according to Eq. 8 rendering Mg^{2+}, Al^{3+} and Fe^{2+} soluble with silicon precipitating to some extent. Some colloidal silica is also formed according to Eq. 9. Colloidal silica has been known to actively forms crud in solvent extraction processes [6] while silicon compounds in ion exchange coat the resin beads [7] used in ion exchange plants, and therein reducing the resin's loading capacity.

$$(Mg_{0.66}Fe_{0.34})_5Al(Si_3AlO_{10})(OH)_8(s) + 5H_2SO_4\,(aq) \rightarrow$$

$$3.33MgSO_4(aq) + 1.67FeSO_4(aq) + Al_2SiO_5(s) + 2SiO_2(s) + 9H_2O(\ell) \qquad (8)$$

$$SiO_2(s) + 2H_2O(\ell) \rightarrow H_4SiO_4(aq) \qquad (9)$$

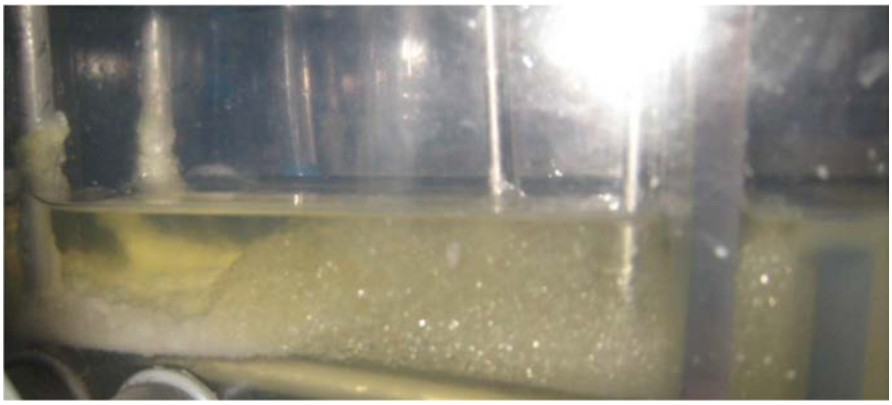

FIG. 2. Crud in solvent extraction, bench-top scale.

3.9. Clays

Clay gangue minerals such as kaolinite can react with acid resulting in elevated acid consumption rates. The reaction of kaolinite with acid is as shown in below (Eq. 10).

$$Al_2Si_2O_5(OH)_4(s) + 3H_2SO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + 2SiO_2(s) + 5H_2O(\ell) \qquad (10)$$

4. PROCESS ENGINEERING CASE STUDY

A case study has been chosen to demonstrate how mineralogy can be use in process engineering. Analyzing the mineralogy of the ore and residues enables the basic framework for the process engineering to be developed.

4.1. Ore mineralogy

The following are the key points of the ore mineralogy for the case study:

1) Ore uranium grade is 400 ppm U;
2) The distribution of uranium mineralogy is as shown in Fig. 3;
3) The contribution of the gangue mineralogy is as shown in Fig. 4;
4) The mineralogy shows the following:

— Uranium is coarse grained with the exception of the uranium minerals in the fine-grained intergrowth. The fine uranium intergrowth consists of fine-grained uraninite, coffinite and brannerite minerals embedded with gangue minerals;
— Upgrade potential is low because uranium is distributed over all particle size distribution (refer to Fig. 5);
— Batch leach test by size were performed and the economic particle size were set at P_{80} 710 µm;
— Micro-fracturing was noticed as a consequence of the crushing tests leaving access for lixiviant (refer to Fig. 6). The mineralogy shows that brannerite was left untouched while uraninite and coffinite were partially leached with lixiviant accessed via pores and capillaries.

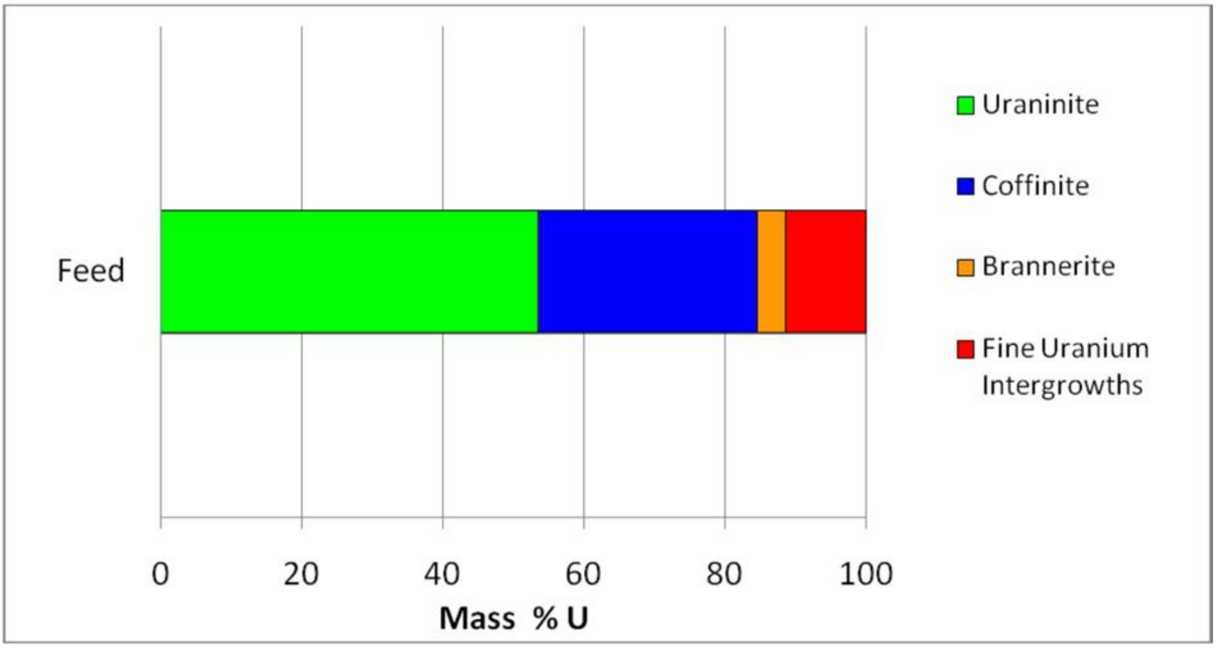

FIG. 3. Uranium minerals distribution in feed.

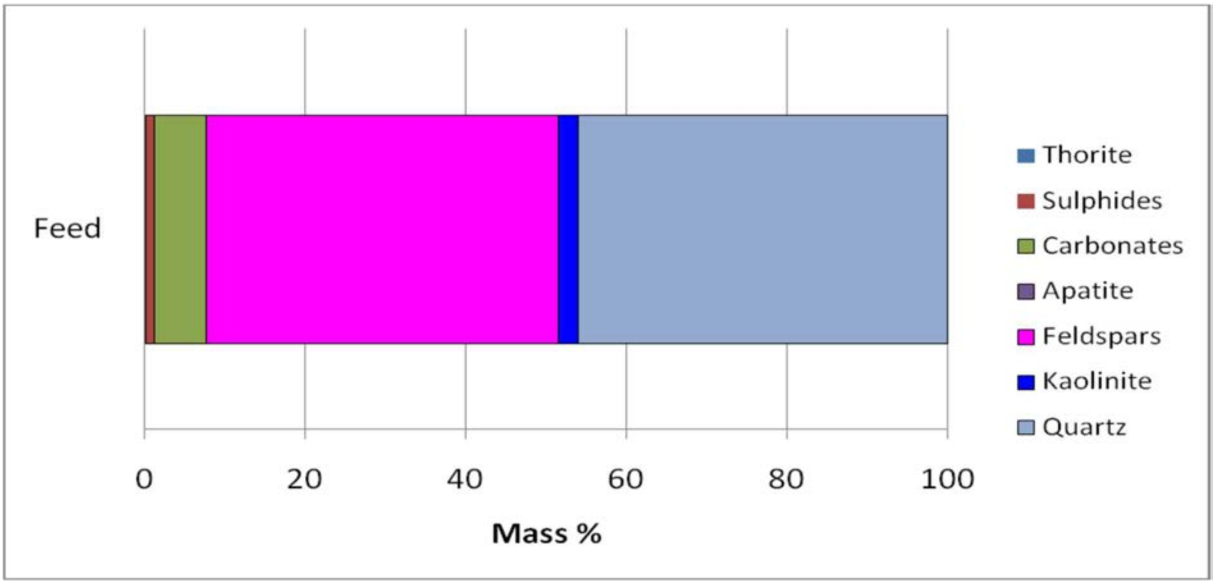

FIG. 4. Gangue minerals distribution in feed.

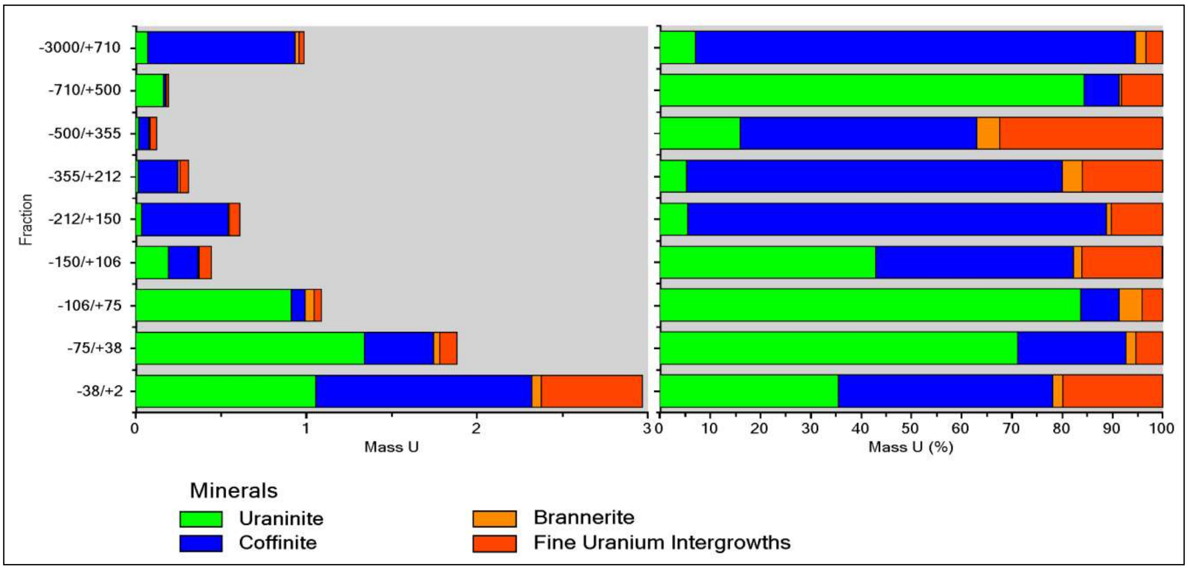

FIG. 5. Uranium size by assay.

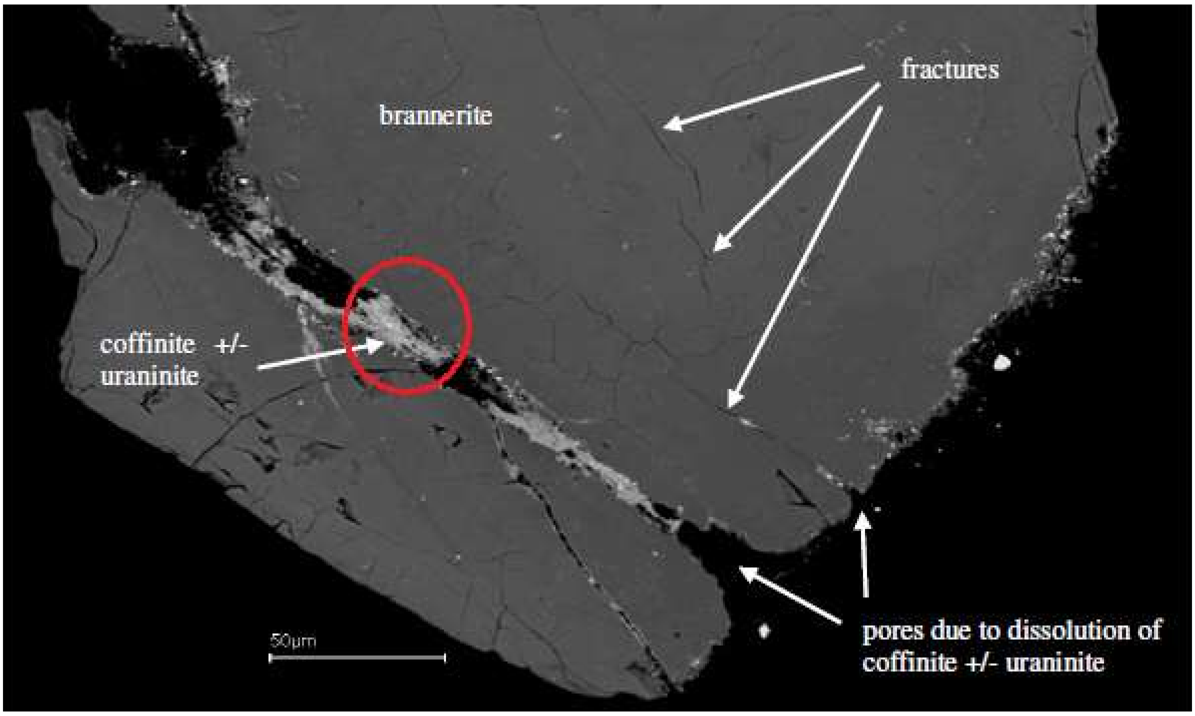

FIG. 6. Back-scattered electron-scanning electron micronscope (BSE SEM) image of a brannerite leach residue particle with micro-fractures and fine uranium intergrowth in the pores.

4.2. Comminution

The mineralogy affects the process equipment and process route chosen for this case study. The flowsheet for this case study is as shown in Fig. 7.

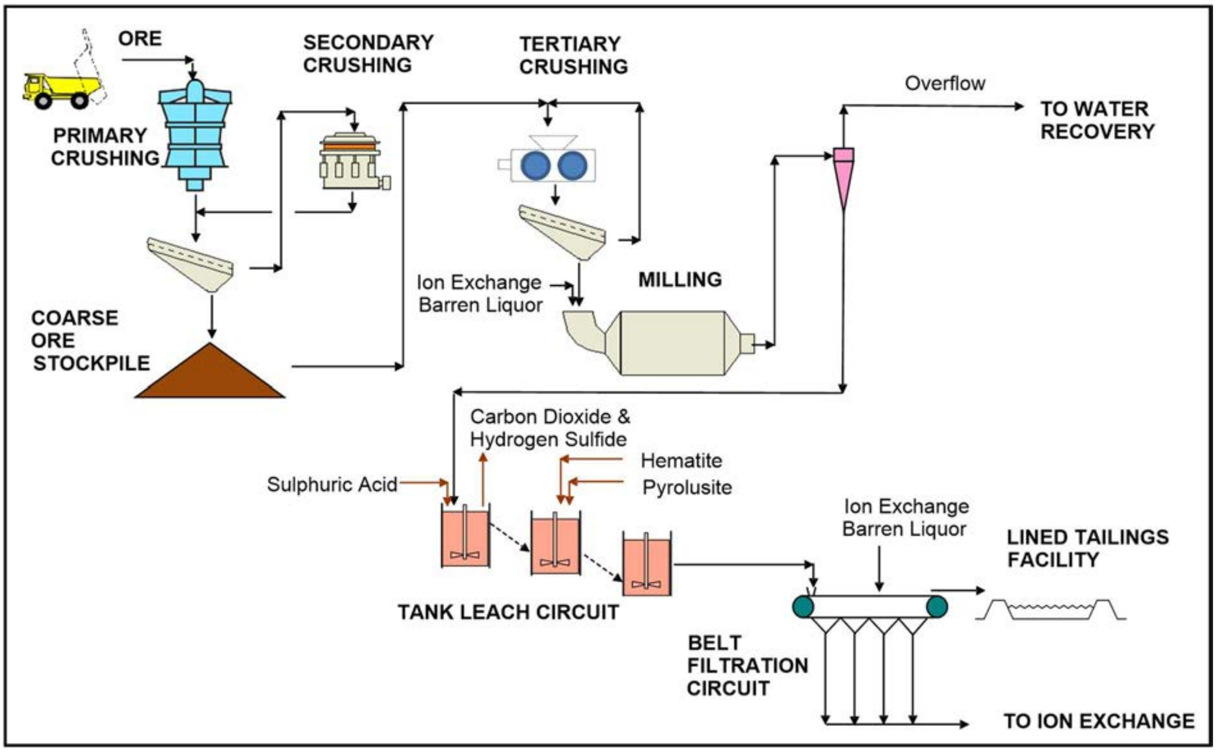

FIG. 7. Case study flowsheet.

In this case study, the comminution circuit selected is three-stage crushing, with HPGR as the tertiary crusher, followed by open circuit ball milling to produce a product size of P_{80} 710µm. This comminution circuit was chosen based on the following reasons:

- HPGR is employed as tertiary crusher to generate micro-fractures in gangue and uranium minerals to enable lixiviant to penetrate through the micro-fractures to leach the uranium in fine uranium intergrowth (refer to Fig. 6);
- The majority of uraninite, coffinite and brannerite grain size are relatively coarse with the exception of the fine uranium intergrowth.

4.3. Leach

An atmospheric acid tank leach process was selected in this case study. The outcome from mineralogy has resulted in the following features in the leach circuit:

1) P_{80} of 710 µm:
   The discovery of uraninite and coffinite leaching as a result of micro-fractures allowing lixiviant access prompted coarser particle size leaching in conjunction with an HPGR circuit which promotes micro-fracturing. In the batch leach testing phase, several tests were conducted examining leach by size. A simple trade off study was conducted in which it was decided to employ a P_{80} of 710µm;
2) Degassing tank ahead of leach circuit:
   The mineralogy of the ore revealed the presence of carbonates and pyrrhotite (Fe_7S_8) in the ore and these species reacts with sulphuric acid to form carbon dioxide and hydrogen sulphide gases (refer to Eqs 10 and 11). Agitated degassing tank with up pumping impeller has been included in the leach circuit to remove these gases. Ferric

sulphate and pyrolusite oxidant are added into the second leach tank, after the degassing tank.

$$CaCO_3\,(s) + H_2SO_4\,(aq) \rightarrow CaSO_4\,(aq) + CO_2\,(g) + H_2O\,(\ell) \qquad (11)$$
$$Fe_7S_8\,(s) + 7H_2SO_4\,(aq) \rightarrow 7FeSO_4\,(aq) + 7H_2S\,(g) + S\,(s) \qquad (12)$$

4.4. Leaching at a high slurry density

The coarse particle size (P_{80} 710 μm) chosen in this case study has resulted in the need to operate the leach at a high slurry density of 70% solids to keep the coarse particles in suspension. One of the benefits of operating the leach at high slurry density is the high solute concentration in the leachate. A photograph showing high slurry density agitation is shown in Fig. 8.

FIG. 8. High slurry density agitation.

4.5. Mass balance

In addition to using mineralogy to predict the process route, mineralogy together with the chemical assays is used to form the basis of the mass balance modelling.

Building the mass balance based on mineralogy has several advantages and these are:

- Enables the species present in the process to be tracked from feed to residue;
- Enables reagents consumption rates to be calculated based on known reaction mechanisms;
- Enables different process conditions to be modeled.

The mineralogy of the leach residue was examined and the following were found:

1) The distribution of uranium mineralogy in the feed and leach residue are as shown in Fig. 9;
2) The contribution of the gangue mineralogy in the feed and leach residue are as shown in Fig. 10.

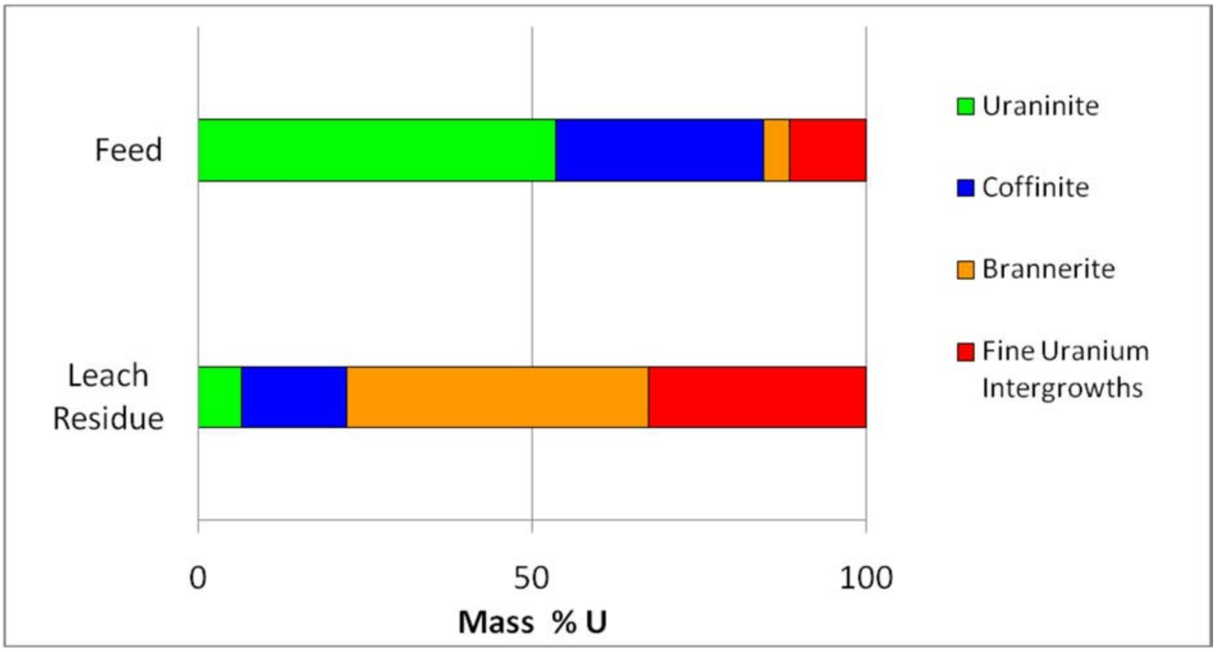

FIG. 9. Comparison of uranium minerals distribution in the feed and leach residue.

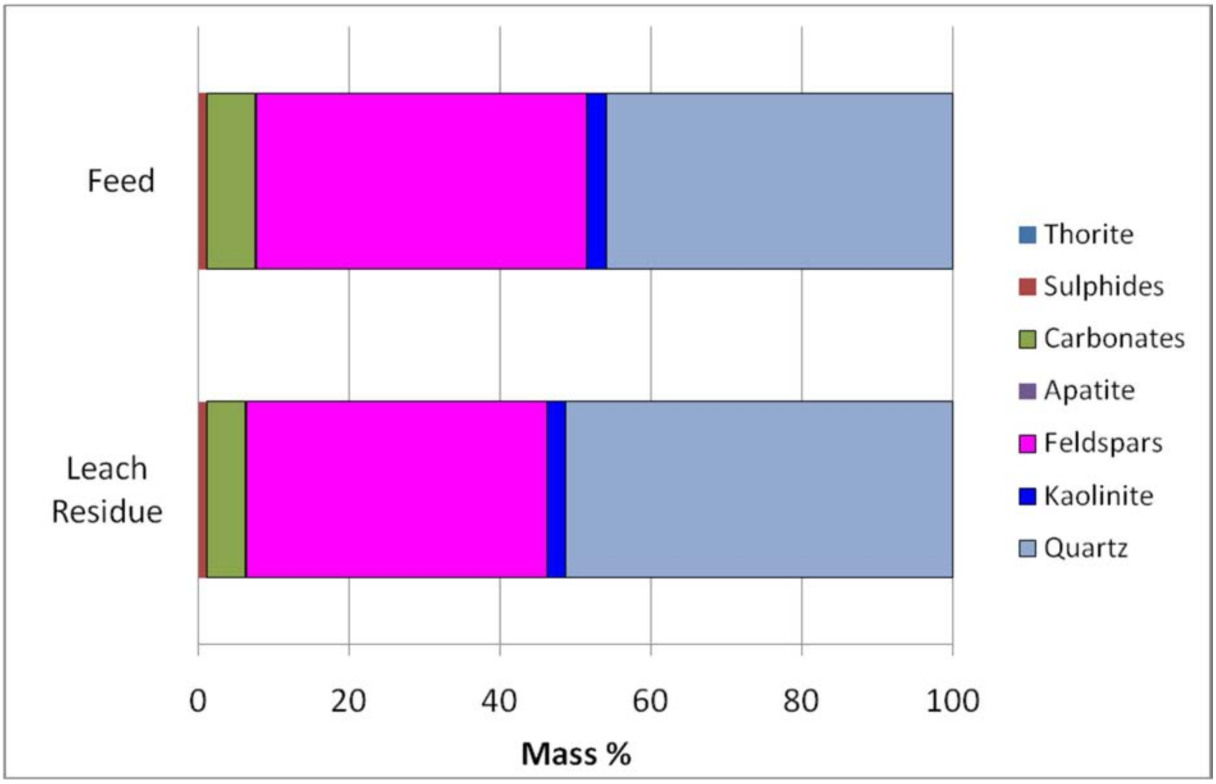

FIG. 10. Comparison of gangue minerals distribution in the feed and leach residue.

4.6. Mass balance feed input

The minerals composition and its distribution in the feed are used as the input to the mass balance model. The mass balance input for the case study is as shown in Table 3.

TABLE 3. CASE STUDY MASS BALANCE MINERALOGY INPUT

Mineral	Distribution (%w/w)	Formula
Uraninite	0.027	UO_2
Coffinite	0.019	$U(SiO_4)_{1x}(OH)_{4x}$
Brannerite	0.003	$(U,Ca,Ce)(Ti,Fe)_2O_6$
Thorite	0.02	$ThSiO_4$
Sulphide (pyrrhotite)	1.1	Fe_7S_8
Carbonate (calcite)	6.4	$CaCO_3$
Apatite (fluoroapatite)	0.15	$Ca_5(PO_4)_3F$
Feldspar (albite)	44	$Na(AlSi_3O_8)$
Kaolinite	2.5	$Al_2Si_2O_5(OH)_4$
Quartz	46	SiO_2
Total	100	

4.7. Establishing leach reactions

The reaction extents of the leach are determined from the following:

- Feed and leach residue mineralogy;
- Feed and leach residue elemental assays.

The mass balance input for leach reactions and extents for the case study is as shown in Tables 4 and 5.

TABLE 4. CASE STUDY URANIUM MINERALS LEACH REACTION EXTENT

Uranium minerals chemistry	Reaction extent	
	Unit	Value
Uraninite		
$UO_2(s) + Fe_2(SO_4)_3(aq) + 2H_2SO_4(aq) \rightarrow H_4UO_2(SO_4)_3(aq) + 2FeSO_4(aq)$	%	99
Coffinite		
$USiO_4(s) + Fe_2(SO_4)_3(aq) + 2H_2SO_4(aq) \rightarrow H_4UO_2(SO_4)_3(aq) + 2FeSO_4(aq) + SiO_2(s)$	%	95
Brannerite		
$UTi_2O_6(s) + Fe_2(SO_4)_3(aq) + 2H_2SO_4(aq) \rightarrow H_4UO_2(SO_4)_3(aq) + 2FeSO_4(aq) + 2TiO_2(s)$	%	1.5

TABLE 5. CASE STUDY MAJOR GANGUE MINERALS REACTIONS AND REACTION EXTENT

Gangue minerals chemistry	Reaction extent	
	Unit	Value
Reaction in the first leach tank		
Calcite leaching		
$CaCO_3(s) + H_2SO_4(aq) \rightarrow CaSO_4(aq) + H_2O(\ell) + CO_2(g)$	%	21
$CaSO_4(aq) + 2H_2O(\ell) \rightarrow CaSO_4.2H_2O(s)$	g/L Ca	0.64
Sulphide (pyrrhotite) leaching		
$Fe_7S_8(s) + 7H_2SO_4(aq) \rightarrow 7FeSO_4(aq) + 7H_2S(g) + S(s)$	%	1
Reaction in the second and subsequent leach tanks		
Ferric generation (with reagents)		
$Fe_2O_3\ (s) + 3H_2SO_4\ (aq) \rightarrow Fe_2(SO_4)_3(aq) + 3H_2O(\ell)$	%	100
$MnO_2(s) + 2FeSO_4(aq) + 2H_2SO_4(aq) \rightarrow Fe_2(SO_4)_3(aq) + MnSO_4(aq) + 2H_2O(\ell)$	%	99
Reaction in all leach tanks		
Albite leaching		
$2NaAlSi_3O_8(s) + H_2SO_4(aq) \rightarrow Na_2SO_4(aq) + Al_2SiO_5(s) + 5SiO_2(s) + H_2O(\ell)$	%	9
$Al_2SiO_5(s) + 3H_2SO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + SiO_2(s) + 3H_2O(\ell)$	%	1.65
$SiO_2(s) + 2H_2O(\ell) \rightarrow H_4SiO_4(aq)$	Δg/L Si	2.6
Fluoroapatite leaching		
$6Ca_5(PO_4)_3F(s) + 6H_2SO_4(aq) \rightarrow 7Ca_3(PO_4)_2(s) + 6CaSO_4(aq) + 3CaF_2(s) + 4H_3PO_4(aq)$	%	31
Kaolinite leaching		
$Al_2Si_2O_5(OH)_4(s) + 3H_2SO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + 2SiO_2(s) + 5H_2O(\ell)$	%	1
Thorite leaching		
$ThSiO_4(s) + 2H_2SO_4(aq) \rightarrow Th(SO_4)_2(aq) + 2H_2O(\ell) + SiO_2\ (s)$	%	64

4.8. Reagent consumption

The reagents consumption rates can be calculated from the uranium and gangue minerals reactions established from the mineralogy and the leach assays. The consumption rates of the leach reagent calculated from the case study mass balance is shown in Table 6.

TABLE 6. REAGENT CONSUMPTION IN LEACH

Reagents	Consumption (kg/dry tonne ore)
Sulphuric acid (H_2SO_4)	27
Pyrolusite (MnO_2)	1.4
Hematite (Fe_2O_3)	1.0

4.9. Impact on effluent

The chemical composition in the tailings is dependent on the ore mineralogy and the leach conditions employed. The leach reactions of the uranium and gangue minerals shown in Tables 4 and 5 can provide information of the species that will report to the effluent. The effluent liquor composition for the case study is as follows:

— Total dissolved solids concentration of 56 g/L;
— Total sulphates concentration of 39 g/L.

The major species of note in the effluents are as shown in Table 7.

TABLE 7. EFFLUENT SPECIES

Effluent species	Process engineering considerations
Hydrogen sulphide and carbon dioxide gas	Gas scrubber in leach tank 1
Th, Al, Fe, Mn, K, Mg, F, Cl, P (aqueous)	Dissolved solutes in the process are removed from the process as interstitial fluid in the belt filter residue to prevent buildup. Ion exchange barren liquor containing these solutes is used as wash liquor in the belt filtration circuit

5. CONCLUSION

A good understanding of the composition of the feed and residue with respect to the uranium and gangue mineralization is imperative to establish the following:

- Basis for the design of the processing plant;
- Selection of process equipment for the preparation of the ore for the leach;
- Optimizing the leach process with respect to reagent consumption and uranium yield;
- An essential basis for the development of mass balances for uranium recovery processes.

Furthermore, the ore mineralogy provides an early understanding of what the liquid and solid effluent could comprise.

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ROLE OF TEST WORK IN PROCESS ENGINEERING OF URANIUM CIRCUITS[28]

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Abstract

Uranium is found in nature in a variety of minerals within ores at different grades, from the very high grade of the Canadian deposits to low grade ores found in Asia, Australia and Africa. This paper examines the options available in flowsheet selection and the role of test work in two uranium case studies.

1. INTRODUCTION

Uranium is found in nature in a variety of minerals and at different grades within ores. Grades vary from the very high grades of the Canadian deposits (e.g. 15–20% U_2O_3; ~13–17% U) at McArthur River and Cigar Lake to low grade deposits such as the Australian Olympic Dam and the Namibian Rössing Mine (<0.1% U_2O_3; <~0.08% U), with Key Lake in Canada, at 2.5% U_2O_3 (~2.1% U) representing the medium grade ore deposits.

Invariably all ores require processing which, in general terms, include:

- Ore preparation;
- Leaching;
- Solid–liquid separation to separate the pregnant leach solution (PLS) from the leached solids;
- Uranium recovery from the PLS and precipitation (Fig. 1).

This paper examines the options available for flowsheet selection and the role of test work in defining the process design. Two case studies will be presented.

Case Study 1 is a uranium project located in the southern hemisphere. This case will be referred for the following unit operations:

- Leaching;
- Solid–liquid separation;
- Uranium recovery;
- Product precipitation.

Case Study 2 is a uranium project located in the northern hemisphere. This case will be referred for the ore preparation unit operation.

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[28] Presented at the Technical Meeting on Uranium Production Cycle Pre-Feasibility and Feasibility Assessment, 7–10 October 2013, Vienna, Austria.

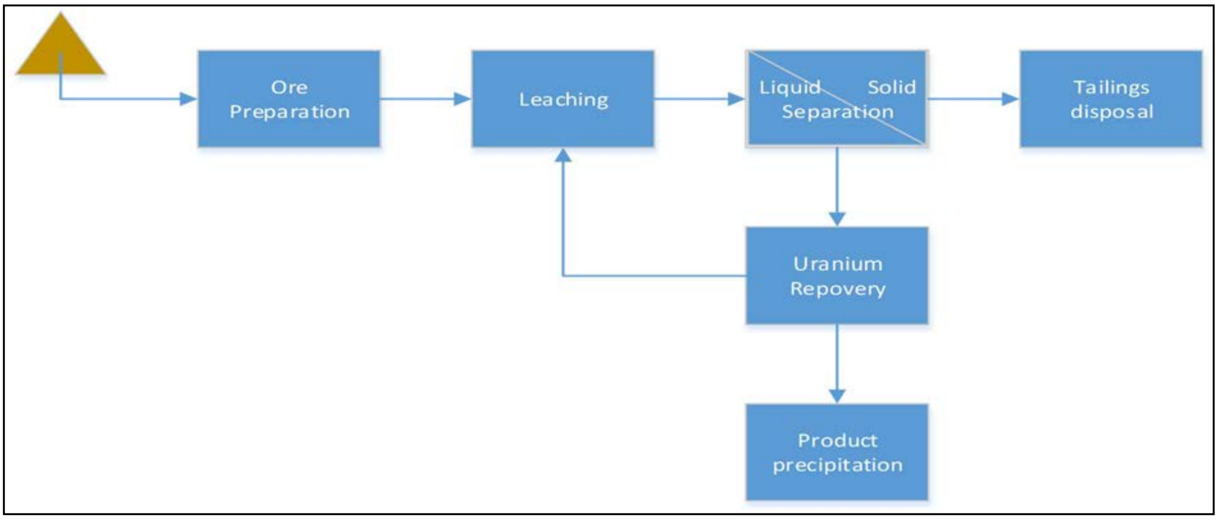


FIG. 1. Generalized uranium process block flow diagram.

2. TEST WORK AND PROJECT DEVELOPMENT STAGES

The extent of test work and therefore the resources required for test work increase as the project progresses through the typical project development stages (Fig. 2). The objective of test work is to provide information that allows understanding of the process at a level of risk that is acceptable for the respective stage. While there may be no need for test work apart from ore characterization at pre-concept stage, pilot plant campaigns are a common requirement for a bankable feasibility study.

Each project is different and therefore its test work requirements need to be tailored to address the particular project specific risks. Table 1 shows what would be considered adequate for each stage of development for a generic project. Test work requirements for each individual project vary according to particular risk areas of the process flowsheet, environmental and regulatory requirements and internal or financing requirements.

Test work for the case studies presented in this paper corresponds to the test work requirements of a pre-feasibility or a feasibility study.

3. ROLE OF TEST WORK IN PROCESS ENGINEERING

3.1. Ore preparation test work

The main objective in ore preparation is to liberate the target uranium minerals so they become available for lixiviation. Sometimes ore preparation includes physical separation and removal of gangue minerals in order to reduce reagent consumption rates in the leaching stage.

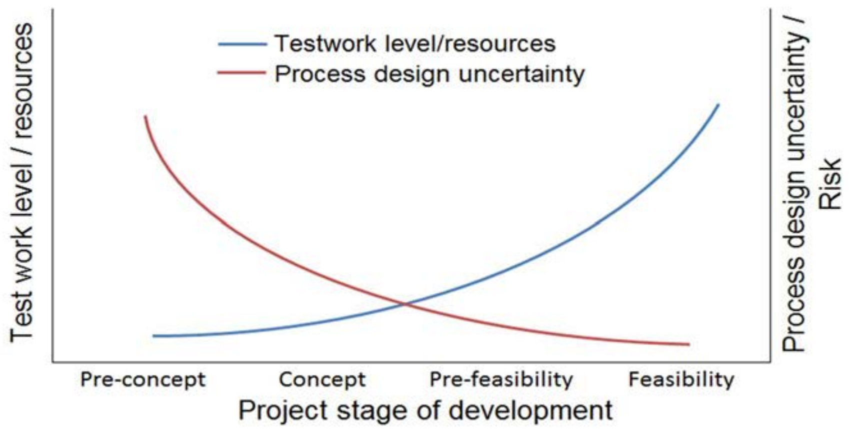


FIG. 2. Role of test work on process design risk.

Ore preparation is heavily influenced by the mineralogy of the ore to be treated and the nature of the uranium minerals within the ore. Mineralogy provides the engineer with an understanding of what process steps can be employed to recover the uranium from its ores. This includes information about:

— Particle size distribution at which minerals are liberated;
— Extent of locking, i.e. grain size of uranium within the host mineral;
— Potential for upgrade and rejection of reagent consuming gangue.

3.1.1. Comminution

Ore preparation involves breaking the ore from the 'run of mine' (ROM) material to a size that allows the lixiviant to get into contact with the target uranium mineral, a process also known as liberation.

Key to the appropriate design of the comminution circuit is the determination of the energy required to break the rock to the target size. A series of standard laboratory scale tests to determine different breakage indices are widely used in the industry for this purpose. These include Crushing index (Ci), Bond Ball Work index (BWi), Bond Rod work index (RWi) and Semi-Autogenous Grinding (SAG) Mill Comminution (SMC) test. A complete comminution characterization requires approximately 200 kg of sample in the form of either rock chips or PQ core (85 mm diameter).

The comminution characteristics of the ore can be used to accurately predict the overall specific energy (kWh/t) requirements of circuits containing Autogenous and (SAG) Mills, Ball Mills, Rod Mills, Crushers and High Pressure Grinding Rolls (HPGRs).

Other specific equipment may require particular vendor test work in order to determine their specific energy requirements.

An example of comminution equipment is shown in Fig. 3.

TABLE 1. TEST WORK AND PROJECT DEVELOPMENT STAGES

Stage of development	% Completed engineering	% Estimate accuracy	Test work guidance
Proof of concept	0	+/– 50	• Minimum test work • General ore characterization and mineralogy • Single batch leach test
Concept	0	+30, –15	• Batch test work of the extraction process • Mineralogy of metallurgical domains
Pre-feasibility	0 – 30	+25, –15	• Comminution test work (laboratory scale) • Laboratory scale test work of one or more potential extraction methods (batch and batch lock cycle) and all critical process unit operations • Variability comminution test work • Preliminary work on uranium recovery options • Geochemistry test work
Feasibility	30 +	+15, –10	• Variability test work (laboratory scale, batch) • Batch test work on composite • Pilot plant - Continuous extraction process - Recirculation close loops - Comminution - Extraction • Key vendor equipment test work (laboratory scale) • Uranium recovery and precipitation test work (batch) • Calibrated mass balance • Residue geochemical test work • Geotechnical test work on tailings • Demonstration plant (recommended for novel processes)

3.1.2. Comminution challenges of case study 2

Case Study 2 required the pre-crushed feed ore (44 mm) to be further reduced to a target P_{80} size of 810 micron at a rate of approximately 450 tph. Table 2 shows the comminution characteristics of this ore determined by test work.

FIG. 3. Example of Comminution Equipment (SAG Mill, courtesy of Orway Mineral Consultants Pty).

TABLE 2. SUMMARY OF COMMINUTION TEST WORK RESULTS – CASE STUDY 2

Parameter	Unit	Value	Notes
Unconfined Compressive Strength (UCS)	MPa	N/A	
Abrasion index (Ai)		0.142	Abrasiveness similar to quartz
Crush work index (CWi)	kWh/t	15.0	Medium to soft material
Bond rod work index (RWi)	kWh/t	22.5	Above average competency
Bond ball work index (BWi)	kWh/t	14.7	Average competency ore
SAG mill comminution (SMC) – parameter A*b		29.0	Medium to hard ore
SAG mill comminution (SMC) – parameter ta		0.27	Medium to hard ore
Ore Specific Gravity (SG)		2.65	

3.1.3. Comminution energy requirements of case study 2

Test work information was then employed to model a comminution circuit designed to achieve the required treatment rate and target P_{80}. The process of circuit selection considered the circuit energy efficiency, product size, size distribution, mill water requirements and operability. The circuit selected for this case study was a partial secondary crushing and a single stage SAG mill. Table 3 shows the specific energy requirements for the selected circuit.

TABLE 3. SPECIFIC ENERGY REQUIREMENT – CASE STUDY 2

Parameter	Unit	Value
New feed rate	tph	450
Feed size, f_{80}	mm	44
Product size, p_{80}	µm	810
Pebble recycle	% feed	25
Crusher feed, f_{80}	mm	40
Crusher product, p_{80}	mm	11
Power utilization		
Sag milling specific energy	kWh/t	12.2
Specific recycle crushing energy	kWh/t	0.20
Total grinding specific energy	kWh/t	12.4
Grinding circuit efficiency, f_{sag}		1.47

Database information and simulation models are employed to interpret test work data for the specific energy requirements and determine the size of the equipment needed. Table 4 shows the recommended size of the comminution equipment for Case Study 2.

3.2. Leaching test work

3.2.1. Chemistry

The two main lixiviants used in uranium leaching are sulphuric acid (major) and sodium carbonate/bicarbonate (lesser). Sulphuric acid leaching is preferred due to higher recoveries and faster kinetics; however, it is non-selective and in ores with high acid consuming gangue minerals use of sulphuric acid results in higher comparative reagent consumption.

Acid leaching of hexavalent uranium (e.g. Autunite) is shown in the following:

$$\mathrm{Ca(UO_2)_2(PO_4)_2.11H_2O + 7H_2SO_4 \rightarrow 2H_4UO_2(SO_4)_3 + CaSO_4 + 2H_3PO_4 + 11H_2O}$$

Ferric is typically employed to oxidize insoluble tetravalent uranium:

$$UO_2 + Fe_2(SO_4)_3 + 2H_2SO_4 \rightarrow H_4UO_2(SO_4)_3 + 2FeSO_4$$

The alkaline leach of hexavalent uranium (e.g. Carnotite) is shown in the following:

$$K_2(UO_2)_2(VO_4)_2.3H_2O + 6CO_3^{2-} \rightarrow 2UO_2(CO_3)_3^{4-} + 2K^+ + 2VO_3^- + 4OH^+ + H_2O$$

Any tetravalent uranium present in the alkaline leach with the hexavalent form requires an oxidant which can be oxygen, air or hydrogen peroxide.

The reagent consumption for uranium recovery is often less than 5% of the total, with gangue minerals consuming the balance of the reagents.

TABLE 4. COMMINUTION EQUIPMENT SELECTION – CASE STUDY 2

Criteria	Units	
Primary crusher		
Crusher type		Jaw
Model		CJ615 or equivalent
Installed motor	kW	200
Secondary crusher		
Crusher type		Cone
Model		CH660 EC or equivalent
Installed motor	kW	290
SAG mill		
Diameter – inside shell	m	8.53
EGL	m	4.80
Imperial	ft × ft	28.0 × 15.7
Shaft power	MW	5.4
Motor power	MW	6.5
Recycle crusher		
Crusher type		Cone
Model		CH440 MF or equivalent
Installed motor	kW	190

3.2.2. Leach regimes

The leach regime is selected to suit both the uranium and gangue mineralogy. Leach test work is required to identify the extraction of uranium and gangue elements and to determine reagent consumption.

The main performance indicators to be derived from test work are:

— Extent of uranium extraction;
— Reagent consumption;
— Extent of gangue mineral dissolution;
— Optimum operating conditions.

Table 5 summarizes the leach regimes most commonly used in the recovery of uranium. Figure 4 shows an example of an in-situ leach operation and Figure 5 shows the view inside a pressure leach autoclave.

FIG. 4. Uranium in situ leach operation (Beverley, South Australia, courtesy P. Woods, IAEA).

FIG. 5. View inside a pressure leach autoclave (courtesy Hydromet Pty Ltd).

3.2.3. Leach test work for case study 1

A continuous agitated acid leach pilot campaign on uranium ore was conducted for over 900 hours to provide a design basis for the hydrometallurgical plant of case study 1.

Prior to the continuous pilot plant campaigns, batch test work was conducted to confirm the optimum process conditions relating to:

— Grind size;
— Temperature;
— Slurry SG.

This work provided information regarding:

— Acid consumption rate;
— Oxidant requirements;
— Residence time.

The batch test work culminated with a trade off study that confirmed an economic optimum at a P_{80} of 710 microns. However, leaching ores with a P_{80} of 710 microns present particle suspension challenges which cannot be addressed in a batch test.

TABLE 5. URANIUM LEACH REGIMES

Leaching regime	Characteristics	Main process design inputs from test work
Heap leach - Mainly used in acid leach; - Some application on alkaline leach.	- Used for low grade ores; - It can be dynamic or permanent heap; - Require a careful environmental review regarding ripios disposal and emergency pond storage capacity; - May involve the oxidation of sulphide gangue minerals for the production of acid.	- Uranium gangue extraction extent; - Acid/alkali and oxidant consumption rates; - Leach cycle time; - Irrigation rate; - Heap height; - Permeability.
In situ leach - Acid and alkaline leach.	- Applied to shallow sandstone aquifers, confined by low permeability shale, in safe location away from groundwater; - Applied where aquifers are unsuitable for human or animal consumption.	- Uranium gangue extraction extent; - Acid/alkali and oxidant consumption rates; - Leach cycle time; - Irrigation rate; - Test work focuses on characterization of ground conditions and aquifer characteristics – hydrogeology is of paramount importance.
Agitated tank leaching - Acid or alkaline; - High temperature (typically >70°C acid or >90°C alkali leach); - Low temperature (typically 20 – 40°C, only acid leach).	- Gas exhaust system needed to remove radon for high grade ores; - Conducted in mechanically agitated tanks or Pachuca tanks; - Feed to leaching may require thickening to achieve a high pulp density in order to achieve a negative water balance.	- Uranium and gangue extraction extent; - Acid/alkali and oxidant consumption rates; - Residence time (6–48 hours); - Pulp density (typically 35–70%); - Temperature.
Pressure leach - Acid (typically 190–210°C); - Alkaline (typically 110–120°C).	- Conducted in horizontal pressure autoclaves; - Faster leaching kinetics and higher extractions than atmospheric leaching; - Lower impurity levels in leach product; - Require expensive materials of construction; - Oxidation via oxygen or compressed air when operating at low temperatures; - May involve the oxidation of sulphide gangue minerals for the production of acid.	- Uranium and gangue extraction extent; - Acid/alkali and oxidant consumption rates; - Residence time; - Pulp density; - Temperature; - Oxygen partial pressure.

The pilot plant was configured to address these above challenges as well as confirm:

— Particle suspension;
— Leach efficiency;
— Reagents consumption rates;
— Materials of construction.

3.2.3.1. Particle suspension

Particle suspension in case study 1 was achieved by increasing the solids content in the slurry above the hinder settling zone at between 68–70% solids w/w using a pitch blade turbine impeller. Test work was conducted using slurries from the pilot plant to determine impeller and tank design parameters. Figure 6 shows a photograph of the agitation test tank and Fig. 7 shows the surface response at slurry densities of 65% (a), 70% (b) and 75% (c).

Agitation test work for case study 1 provided the following information:

— Apparent viscosity: 300–2000 mPa·s;
— Slurry density: 65–70% w/w;
— Specific torque: 37–58 Nm/m^3;
— Power/unit value: 0.6–3.7 kW/m^3;
— Baffle — aspect ratio: 0.10–0.12.

FIG. 6. Test agitation tank (courtesy of Mixtec Pty).

a) Surface response at 75% solids

b) Surface response at 70% solids

c) Surface response at 65% solids

FIG. 7. Surface response during agitation tests — case study 1 (courtesy of Hydromet Pty Ltd).

3.2.3.2. Leaching efficiency

The uranium leach extraction profile of the pilot plant circuit (Fig. 8) for Case Study 1 is shown in Fig. 9.

Leaching pilot plant results provided design criteria for:

— Residence time;
— Uranium extraction;
— Gangue extraction;
— Temperature and pH conditions.

Materials of construction

In addition to leach performance, pilot campaigns are also useful to gain information about materials of construction for equipment exposed to aggressive conditions.

FIG. 8. Atmospheric leach circuit of a pilot plant (courtesy of SGS Pty Ltd).

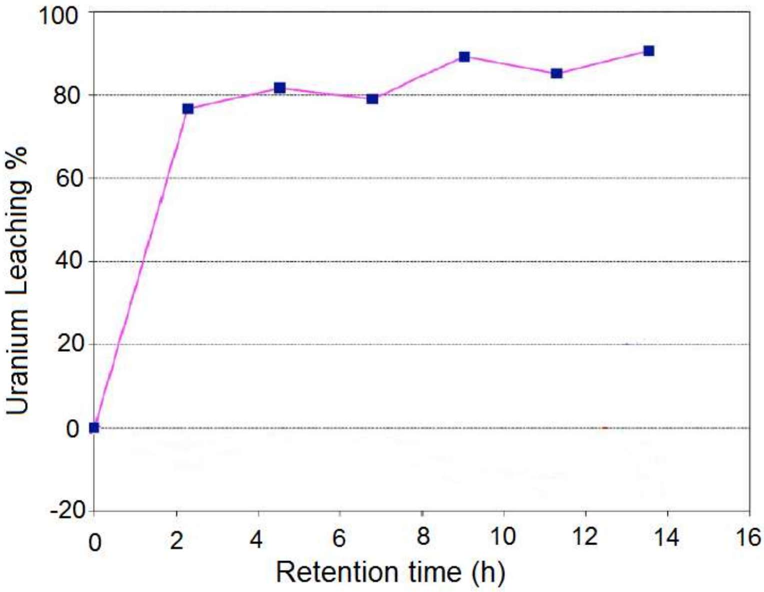


FIG. 9. Overall leach efficiency profile — case study 1.

Alloys tested during the pilot campaign for case study 1 included stainless steel UNS–S31603 and UNS–S30403 as well as alloys UNS–S32001, UNS–S31803, UNS–S32101 and UNS–S40977. With the exception of UNS–S40977, all alloys tested were resistant to the test conditions. Figure 10 shows UNS–S40977 alloy with slight but clearly visible etching or other evidence of attack.

FIG. 10. UNS–S40977 coupon from pilot campaign — case study 1.

3.3. Solid–liquid separation test work

Two systems are used for solid–liquid separation of uranium leach residue:

- Thickeners:
  - Prior to filtration;
  - In lieu of filtration (in a Counter Current Decantation (CCD) arrangement).
- Filtration (with or without thickening):
  - Vacuum belt filtration;
  - Pressure filtration.

Where slurry viscosities are non-Newtonian resin in pulp has been used for uranium recovery, after resin removal the spent slurry is sent to the tailings facility.

3.3.1. Thickeners

Thickening test work is used to determine the type of thickener required and to determine the size of the equipment needed. This vendor specific test work aims to determine the following:

- Feedwell solids content and flocculant dose;
- Flocculant type and addition rate;
- Settling rate;
- Underflow solids content;
- Flux (kg/m^2/h);
- Overflow suspended solids content;
- Bed residence time required for target underflow solids;
- Yield (Pa).

3.3.2. Filters

Filtration test work is used to determine the type of filter adequate for the required duty and determine the size of the equipment required. These vendor specific tests aim to determine the following:

- — Flocculant addition, dose and rate;
- — Flux (kg/m^2/h);
  - Cake formation;
  - Cake washing;
  - Cake drying;
- — Wash efficiency;
- — Cycle time;
- — Cake thickness (> 7 mm).

An example of the general arrangement of a uranium plant thickener and belt filter is shown in Fig. 11.

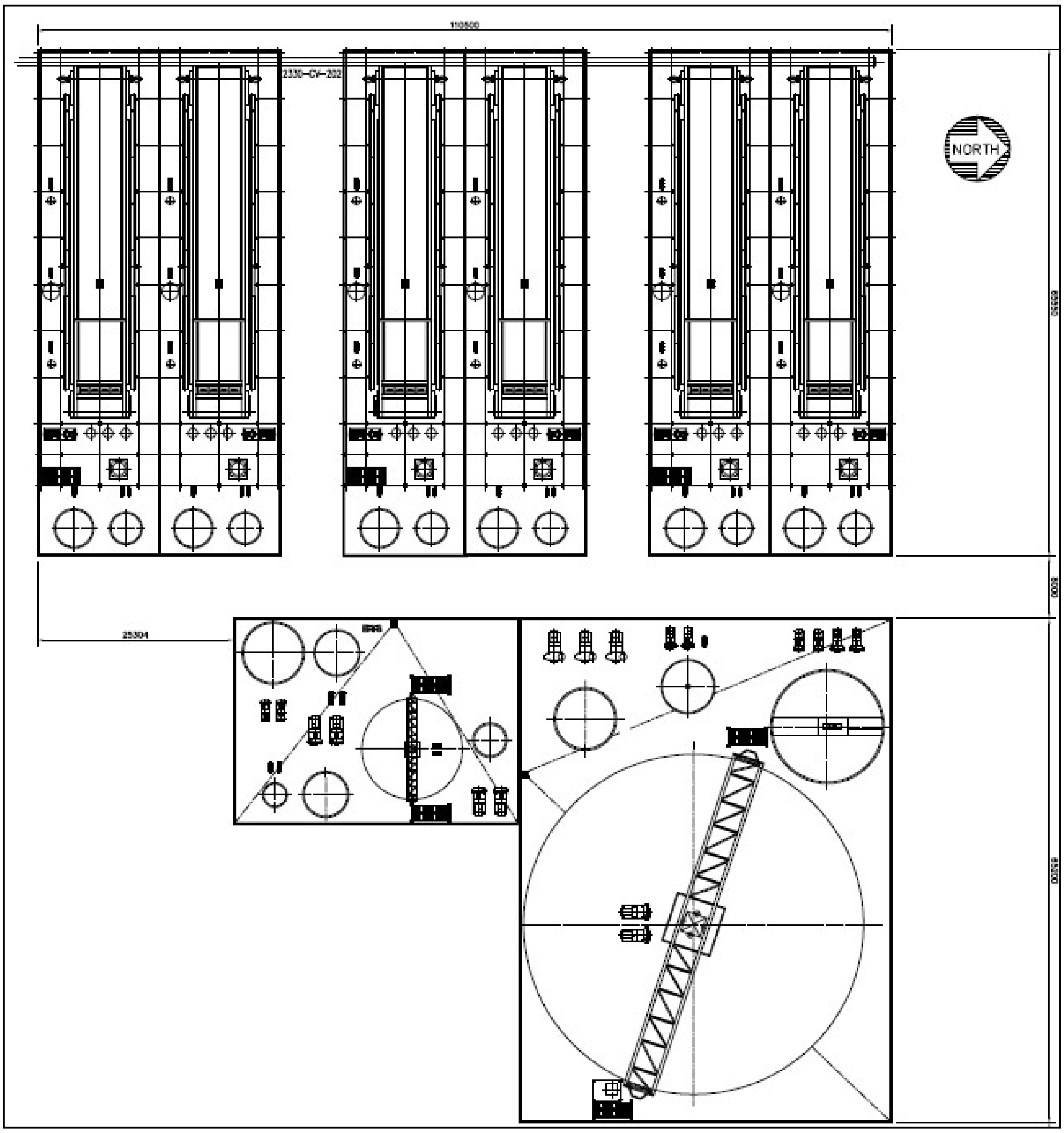


FIG. 11. General arrangement of a thickener and vacuum belt filter.

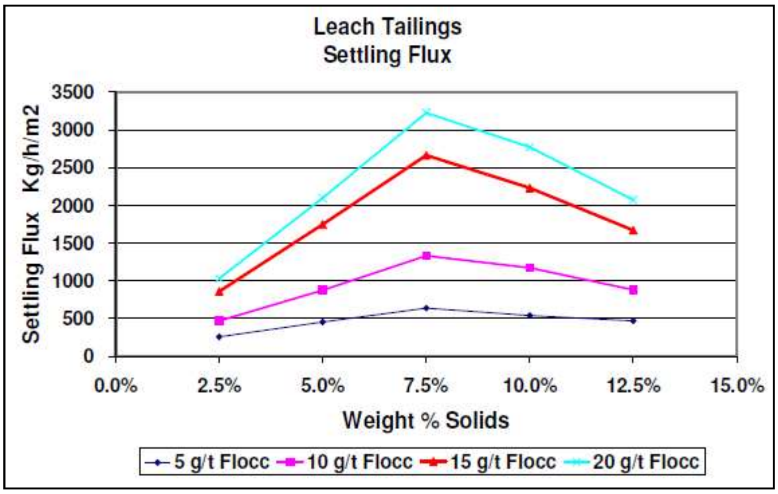
3.3.3. *Solid–liquid separation test work in case study 1*

3.3.3.1. Thickening

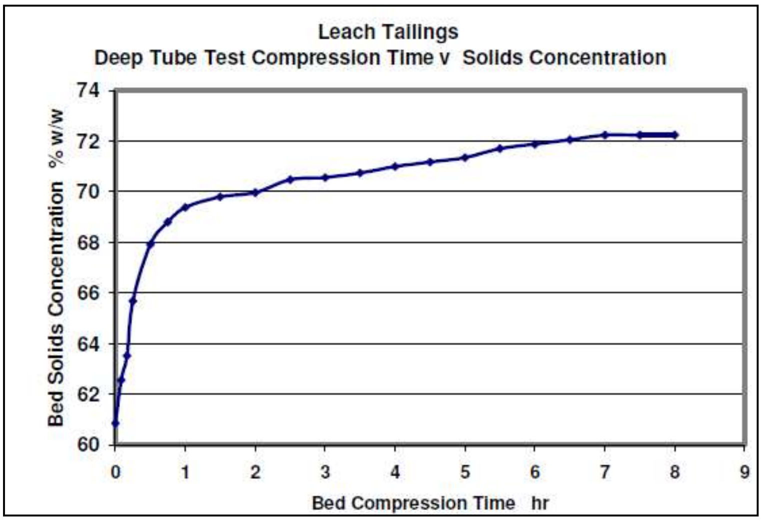
Thickening tests were conducted on uranium leached tailings slurries from the pilot plant campaign. Table 6 shows the test work conducted and the key information from each test used for design.

TABLE 6. THICKENING TEST WORK RESULTS – CASE STUDY 1

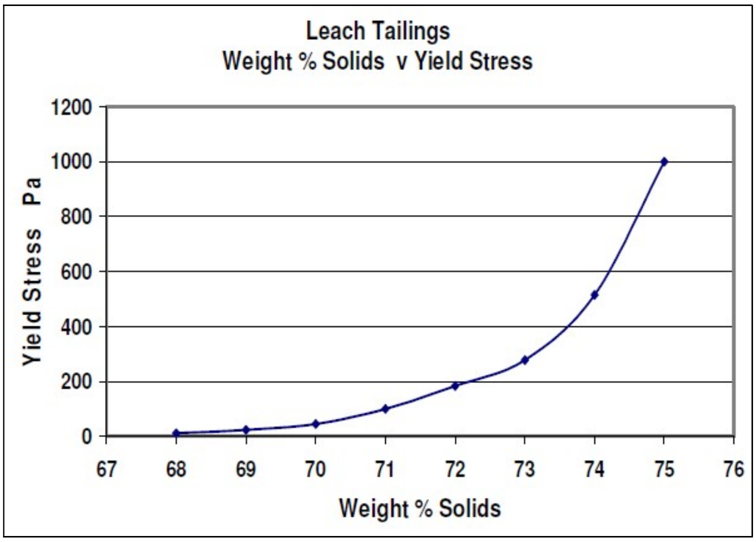
Test	Key test work information for process engineering
Settling flux vs. flocculant dose	The settling flux indicated optimum settling performance at feedwell solids concentrations of 7.5% w/w.



Test	Key test work information for process engineering
Static cylinder test	– Settling rates of 19–56 m/h; – Overflow solids of < 100 mg/L; – Ultimate underflow solids densities of 68.6 w/w–70.8% w/w
Underflow solid content vs. retention time	– Overflow solids: < 150 mg/L; – Rise rate: 8 m/h; – Bed solids:



Underflow rheology



3.3.3.2. Filtration

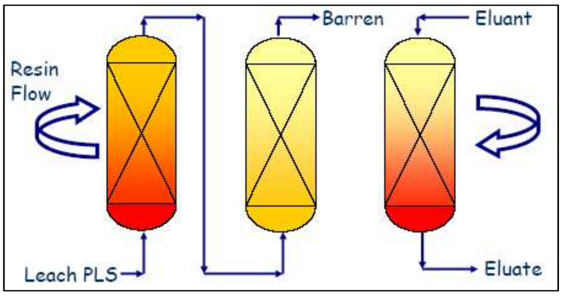
Belt filter test work was conducted on slurries from the pilot plant. Key test work results were:

— Cake moisture:	15–20%
— Drying time:	20 seconds
— Filterability:	1500–1600 kg dry solid/h/m^2
— Expected wash recovery:	> 98%
— Wash ratio:	0.8/ton

3.4. Uranium recovery test work

The following unit operations are employed in recovering uranium from leachates:

- Ion exchange;
  - Fixed bed (Fig. 12);
  - Carousel (Fig. 13);
  - Fluid bed; the fluid bed can be simulated at pilot scale in a cascade set-up (Fig. 14(b)). Commercially, the fluid bed ion exchange systems are constructed in a tower arrangement (Fig. 14(a));
- Solvent extraction;
  - Mixer–settler;
  - Pulsed columns.



Classical lead–lag column arrangement

FIG. 12. Fix bed ion exchange.

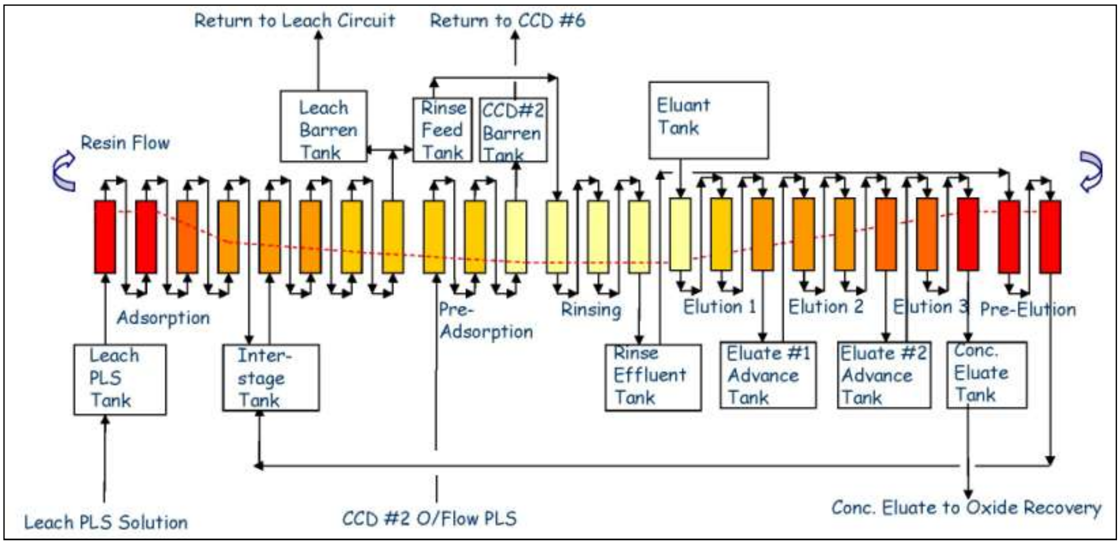


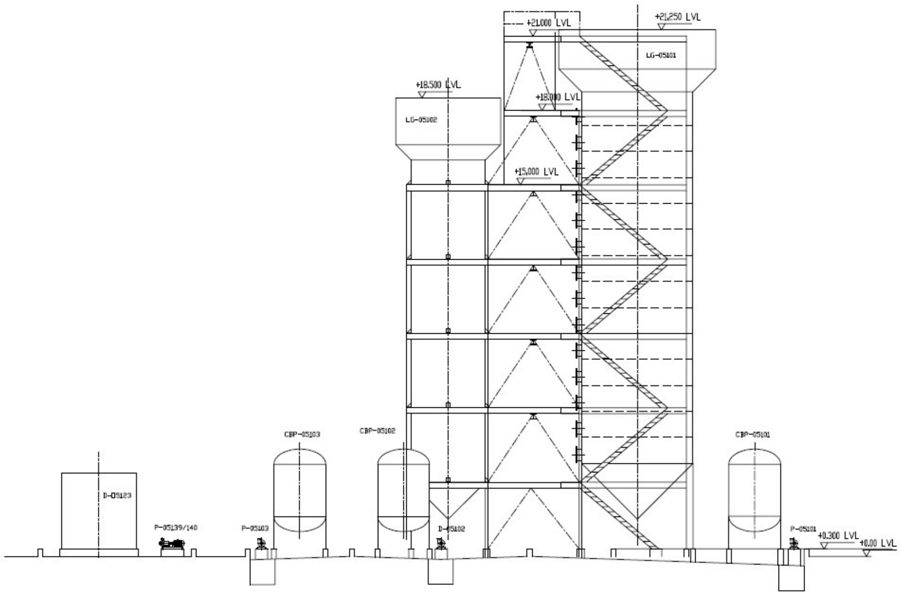
FIG. 13. Typical carousel ion exchange flowsheet.

3.4.1. *Uranium recovery test work in Case Study 1*

3.4.1.1. Ion exchange

The low uranium tenor of the leachate together with its high impurity load predicated the use of a combination of ion exchange and solvent extraction.

The ion exchange circuit was tested at pilot scale with the set-up shown in Fig. 14(b). The high suspended solids in the leachate (around 1000–3000 mg/L) contributed to the selection of a fluid bed system. The resin was eluted with 1.2 molar sulphuric acid.



a) General arrangement of a uranium fluid bed (nimcix).

b) Uranium Pilot Plant Continuous Ion — Simulating Fluid Bed (NIMCIX) (Reproduced with permission from SGS Pty).

FIG. 14. Fluid bed ion exchange.

3.4.1.2. Solvent extraction

The solvent extraction pilot plant had the ion exchange eluate as its PLS. A system consisting of 4 stages of extraction, 2 stages of scrubbing, 3 stages of stripping and one stage of washing was employed.

During piloting, crud formation became pervasive in the extraction circuit and it was discovered to be attributed to suspended solids carried over (Fig. 15). Colloidal silica (Fig. 16) resulted in poor phase separation and a misreport of crud to the entire circuit.

FIG. 15. Crud formation due to suspended solids (Courtesy of Hydromet Pty Ltd).

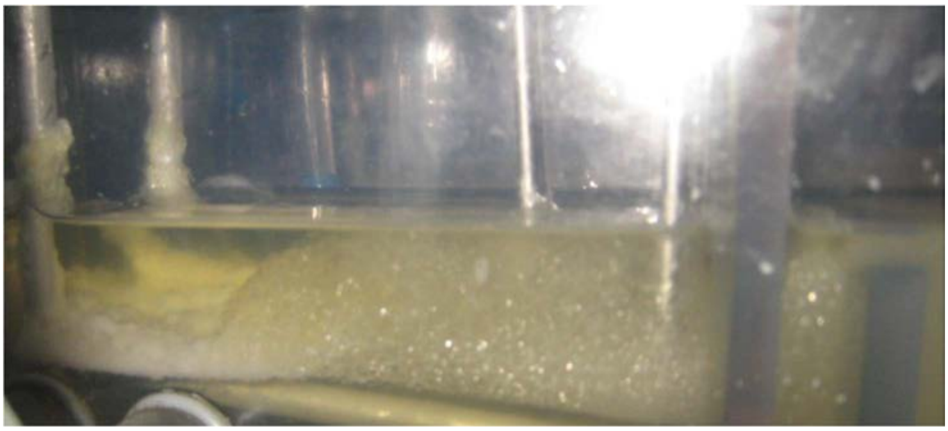


FIG. 16. Crud formation due to colloidal silica (Courtesy of Hydromet Pty Ltd).

3.5. Product precipitation test work

The loaded strip liquors from solvent extraction or the concentrated eluates from ion exchange report to yellow cake product recovery.

Historically, ammonium based processes have been employed:

$$2UO_2SO_4 + 6NH_3 + 3H_2O \rightarrow (NH_4)_2U_2O_7 + 2(NH_4)_2SO_4$$

The ammonium diuranate (ADU) is sometimes calcined to produce mixed uranium oxide U_3O_8.

Environmental concerns related to the use of ammonium reagents have seen the use of the sodium base processes in more recent years:

$$2Na_4UO_2(CO_3)_3 + 6NaOH + 3H_2O \rightarrow Na_2U_2O_7.6H_2O + 6Na_2CO_3$$

The sodium diuranate (SDU) is then dissolved in sulphuric acid

$$Na_2U_2O_7.6H_2O + 3H_2SO_4 \rightarrow 2UO_2SO_4 + Na_2SO_4 + 9H_2O$$

And the resulting uranyl sulphate is converted to uranium tetraoxide:

$$UO_2SO_4 + 2NaOH + H_2O_2 \rightarrow UO_4.2H_2O + Na_2SO_4$$

The ADU/SDU can then be filtered but is more preferably washed in centrifuges prior to product drying/calcining.

3.5.1. Product specification

Product for sale from a uranium ore processing plant needs to meet the requirements and specifications of the converters. Converters place specifications on at least the following elements:

Cadmium, boron, thorium, iron, vanadium, zirconium, molybdenum, sulphate and phosphate.

3.5.2. Product precipitation test work case study (case study 1)

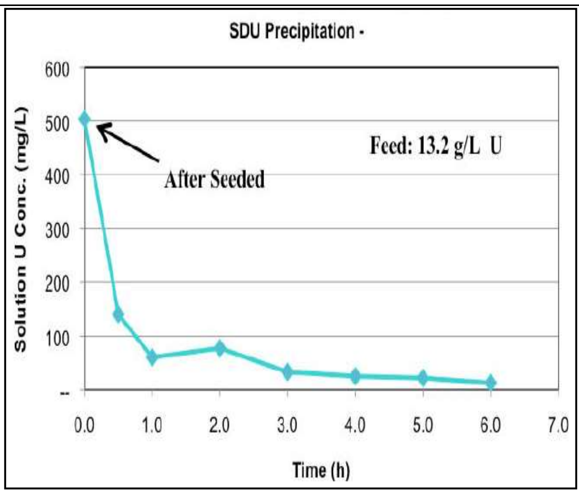
In case study 1, the loaded strip was sodium uranyl tricarbonate. This was converted to SDU and uranium tetraoxide.

Product precipitation test work is generally conducted on a bench scale because of the limited amount of either strip solution or eluant that can be obtained from a piloting campaign. Test work was conducted to determine:

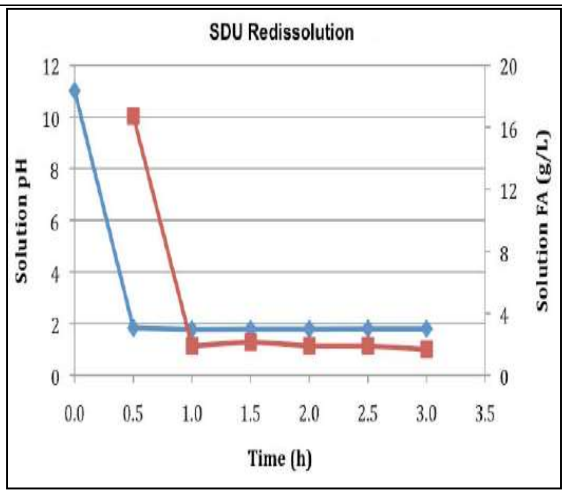
- Reagent dose and consumption rates;
- Residence time;
- Precipitation and dissolution extent;
- Seed recycle requirements;
- Wash efficiency;
- Product quality.

Figure 17 shows the seeded precipitation profile of the SDU (a), the dissolution profile of SDU in weak acid (b), the uranium tetraoxide precipitation profile (c) and a photograph of the uranium tetraoxide obtained after drying (d).

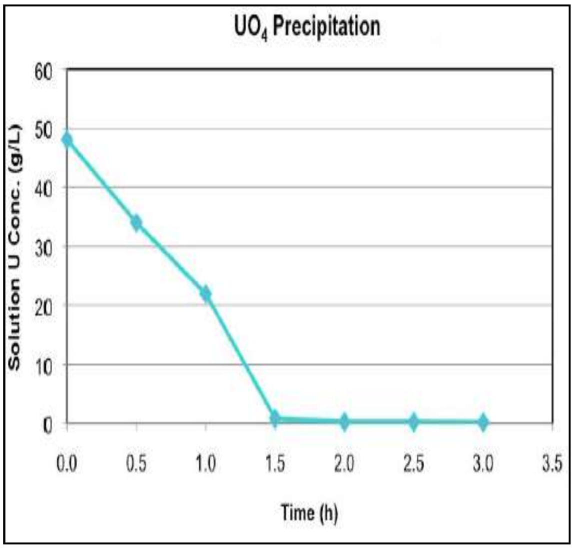
For the case study 1, the UO_4 product typically assayed as shown in Table 7.



a) Batch SDU seeded precipitation profile



b) Batch SDU re–dissolution profile



c) Batch uranium tetraoxide precipitation profile

d) Ground UO_4 sample after drying

FIG. 17. Product precipitation test work results — case study 1.

TABLE 7. TYPICAL PRODUCT ASSAY — CASE STUDY 1

Element	Assay
U	67.0%
K	0.02%
Mn	0.01%
V	0.09%
C	<0.01%
Zr	0.02%
Th	< 0.001%
Fe	< 0.01%
Mo	< 0.0001%
P	< 0.001%

3.6. Effluent test work

Uranium hydrometallurgical plants are required to dispose of their effluents in a responsible manner. Geochemical tests are performed on batch and pilot test work leach residues to confirm and determine the requirements of the final tailings facility.

The liquid and solid fractions of the effluent are tested to provide the following data:

— Electrical conductivity;
— Redox potential (Eh);
— Elemental assay of both the liquid and solid fractions employing ICP–MS;
— pH;
— Acid potential (AP)/Neutralization potential (NP);
— Net acid generating (NAG) characteristics;
— Kinetic test ASTM D5744–96 to examine the leaching kinetics of critical elements;
— Metals mobility leach tests as in toxicity characteristics leaching procedure (TCLP), both short and long term.

4. RADIONUCLIDE CONSIDERATIONS IN PROCESS ENGINEERING

There are unique hydrometallurgical challenges to processing uranium ores and these are related to the presence of the daughter products of uranium and thorium. Figure 18 shows the decay chain of uranium–238.

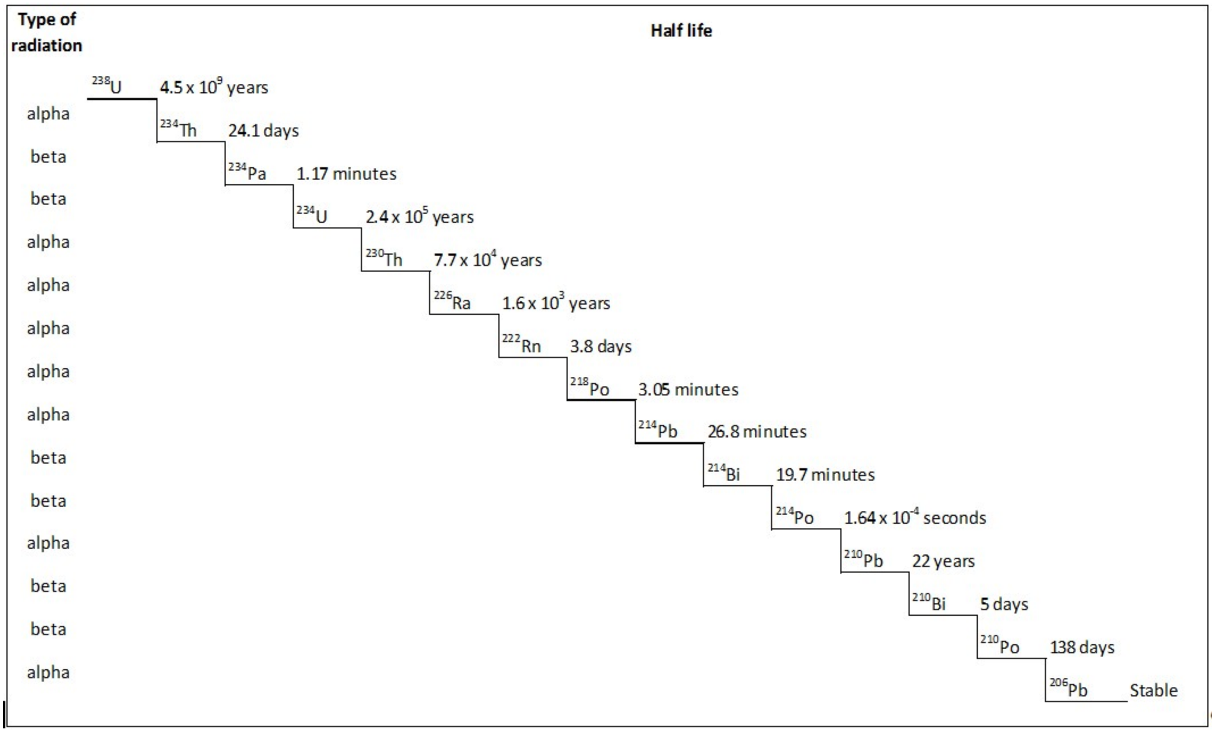


FIG. 18. Natural decay series for uranium–238. Adapted from and courtesy of S. Paulka.

In the comminution stage, particularly in the milling steps, there is potential for the liberation of radon gas. Radon–222 is a gas with a half-life of 3.8 days. It is a decay product from radium–226. Radon–222 gas, while short lived, can cause health issues to workers on uranium plants.

Consequently, in the ore milling circuits and the tank leach process where radon–222 is released, the sealing and safe ventilation of process equipment must be considered (e.g. Fig. 19).

FIG. 19. Example of comminution equipment (SAG Mill, courtesy of Orway Mineral Consultants Pty. Ltd.).

Operators of uranium plants will be aware of, for example:

— Radon–222 gas evolved in the leach should to be ventilated under induced draft;
— Radium–226, bismuth–214 and lead–214 which can precipitate in sludge in the solid–liquid separation equipment;

— Bismuth–214 which has been known to accumulate in solvent extraction circuits including cruds;
— Radium–226 which is often present in the aqueous effluents and can be attenuated by addition of barium hydroxide.

Specialist advice should be sought in the matter of radiation protection.

5. CONCLUSIONS

This paper has examined the options available in flowsheet selection for uranium hydrometallurgical plants and the role of test work in defining the process design and selection. Examples of the role of test work in the process design were presented in two case studies for the main unit operations.

Batch leach test work results provided:

— Ore comminution characteristics to determine specific energy requirements of the comminution circuit and comminution equipment specifications;
— Economic optimum regarding particle size, uranium extraction and reagent consumption.

Batch test work, although valuable at early stages of process development, was insufficient to produce a complete basis of design.

Continuous test work was required to complete the basis of design and allowed for vendors to conduct test work conducive to equipment design and process warranties for specific pieces of equipment (e.g. filters). Continuous test work provided:

— Leach retention time;
— Confirmation of extraction of uranium and gangue elements;
— Confirmation of reagents consumption;
— Solid–liquid separation data;
— Uranium separation data;
— Product characteristics;
— Effluent chemical characteristics;
— Confirmation of mass balance;
— Confirmation of process sustainability.

Batch and continuous test work results provided the basis of design for the process that allowed the project to advance in the project development cycle, progressing into implementation.

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APPLYING THE “SAFETY CONSCIOUS WORK ENVIRONMENT” AT U.S. DEPARTMENT OF ENERGY RADIOACTIVE WASTE CLEANUP SITES[29]

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Abstract

A Safety Conscious Work Environment (SCWE) is a work environment in which employees feel free to raise safety concerns to management (and/or a regulator) without fear of retaliation. Projects with a healthy and mature SCWE are safer, more productive, while creating a higher quality product. Worker moral is higher than traditional projects that lack an applied SCWE. One of the direct benefits to SCWE is the building of trust between management and the workers, and between the workers within the project. SCWE has a direct effect on the success of leadership, the employees and the organization. The Moab Uranium Mill Tailings Remedial Action (UMTRA) Project continues its journey of adapting the SCWE principles to ensure a healthly, safe, and productive work environment.

1. INTRODUCTION

The foundation of applying SCWE is leadership, employee engagement, and organizational learning [1].

The U.S. Department of Energy’s (DOE’s) ultimate safety objective is to have zero accidents, work-related injuries and illnesses, regulatory violations and reportable environmental releases. DOE’s Integrated Safety Management policy is the foundation of our approach to safety and health.

2. COMMITMENT TO SAFETY AND HEALTH

The following precepts reflect our strong commitments to safety and health:

— We have a safety culture built on an environment of trust and mutual respect, worker engagement, and open communication, in an atmosphere that promotes a questioning attitude with effective resolution of reported problems coupled with continuous learning;
— We operate our facilities and conduct work activities in a manner that protects our employees, the public and the environment. We recognize that meeting minimum requirements merely reflects the starting point of our pursuit of excellence and is not the end objective;
— Each one of us is responsible for safety. We strive to ensure that every employee understands his or her role, responsibility, authority and accountability in safely planning, executing and monitoring work performance;
— We foster a SCWE across all departmental operations. Federal, laboratory, and contractor workers have the right to openly identify and raise issues that affect their safety and health or that of their coworkers and without fear of reprisal. We must not deter, discourage or penalize employees for the timely identification of safety, health, environmental, quality or security issues, the reporting of illnesses or injuries, or the use of Employee Concerns or Differing Professional Opinion Programs. Our workers

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[29] Paper first presented at the Technical Meeting of the UMREG in Freiberg, Germany, September 2014 (updated in 2016). Copyright U.S. Department of Energy, published with permission.

receive a prompt, professional, and transparent evaluation and resolution of their concerns;
- We learn from our mistakes and experiences. We report errors and problems, establish vigorous corrective action programs, monitor performance through multiple means, learn from operational experience and encourage a questioning attitude.

3. ESTABLISHING AND SUSTAINING A SCWE

Creating a healthy SCWE is a journey, but one that is well worth the time and effort individuals and their organization must devote to it. A SCWE begins with senior leadership's establishment of behavioural expectations, effectively communicating those behavioural expectations throughout the organization, and visibly practicing those behaviours in the work environment every day.

Actions speak louder than words. This daily visible reinforcement of positive behaviours supports leadership in promoting an open and collaborative work environment.

Sustaining a SCWE requires ongoing vigilance by the organizational leadership. Leaders cannot sit back and rest on their laurels once they believe they have reached the top because there is no top. A learning organization values a questioning attitude and constantly looks for better ways to improve/achieve results [2, 3].

4. WALKABOUTS

Walkabouts, or walking around areas of responsibility, are a great way for a manager to reinforce his/her expectations and improve communications between management and workers. Walkabouts support improved performance by providing direct management observation and oversight of work activities and give a manager a chance to talk directly to employees and get their perspective on how things are going. Walkabouts also create and sustain an open and collaborative work environment.

5. LADDER OF ACCOUNTABILITY

The ladder of accountability is a visual tool that provides an effective way to look objectively at an issue and make deliberate choices about how individuals and their organization want to approach the issue.

The top four rungs describe a stance generally focused on problem solving and movement to the future. Behaviours demonstrated are of holding an individual and each other accountable. The bottom four rungs describe a stance generally focused on sustained conflict and the past. Behaviours demonstrated are those of avoiding accountability.

The more team members choose stances in the top portion of the ladder, the greater the chance of successful collaboration to attain mission objectives and goals.

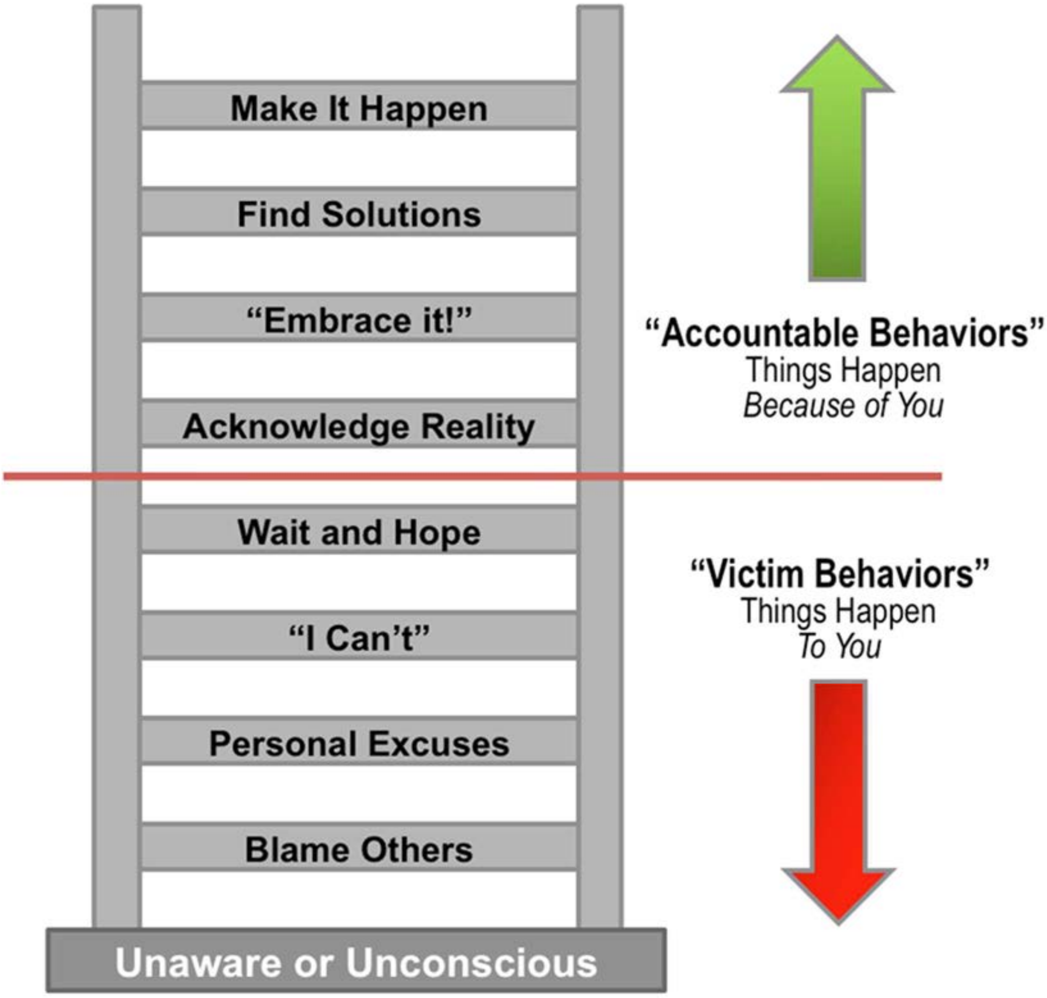

FIG. 1. Ladder of accountability.

6. MANAGER/SUPERVISOR SUGGESTIONS FOR FOSTERING A SCWE

Encourage employees to ask questions, suggest new approaches, offer solutions and raise concerns through any available means.

Be approachable by being available for employees to engage, allow adequate time to talk through issues, and give them undivided attention.

Really listen to employee views and concerns — listen to hear, not to respond and ask clarifying questions to reduce confusion and prevent miscommunication.

Separate the situation/issue identified from the person.

Get clear on the employee's expectations with regard to his or her need for confidentiality. Ask employees if they have a possible solution or option for resolution.

Be prepared to tell the employee what action may or will be taken, when action will be taken, and when feedback will be provided.

Evaluate the issue for any immediate threat to safety or health and the impact of the issue on the individual as well as the workplace (for example, does the situation create a liability to the organization; does the situation create or potentially create a workplace that discourages worker engagement).

Ensure the action or actions are traceable, transparent and responsive to the situation.

Seek assistance, as appropriate, from subject matter experts, such as human resources, labor relations or the Employee Concerns Program.

7. CASE HISTORY

Specific application of SCWE at the Moab UMTRA Project site began a few years ago when DOE Headquarters began placing emphasis on creating a healthy and mature safety environment for all the workers. The first steps were:

1) SCWE awareness among the management team;
2) A clear vision and support from senior management;
3) Adequate training for managers and first-line supervisors;
4) Establishment of the SCWE charter with objectives and goals;
5) Continuous SCWE emphases with all layers of the organization;
6) Rigorous oversight and assessment;
7) Opportunity for employee feedback.

This process started at the Moab Project in late 2013. Even though the project had a long history of good safety statistics, it was apparent to senior management that the Moab Project safety culture was not as mature as the nuclear reactor organizations. Efforts began immediately to raise the bar and implement SCWE. The first step was awareness and training. Senior management began to discuss the origin and where the foundation of SCWE came from, why it is important and what the lasting benefits will look like if applied correctly. Moab Project managers travelled off-site and joined other managers for a detailed and interactive SCWE training. Moab managers were expected to bring their new awareness of SCWE back to the project first-line managers and ensure the principles were immediately applied. Within a number of months, an outside assessment team performed an audit that included a survey of project employees. The goal was approximately 93 per cent of the workforce employees should react positively that SCWE is being fully applied and they feel empowered and free from retaliation to bring up safety related issues or concerns.

Progress was slow in the beginning, but SCWE improvements began to take hold and project employees began behaving freely and openly with their supervisors and management when they have suggestions and or concerns. These days, employees are quick to understand detriments to sustained SCWE such as over-emphases of production without full safety considerations, or sudden arrival of acclimate weather or other changed conditions in the workplace. SCWE integrates well with integrated safety management and the worker who is trained to both is always better adapted to work safely and to look out for and protect his or her coworkers.

The project has found that an active employee safety committee assists greatly as a core tool in sustaining SCWE. On the Moab UMTRA Project, the employee safety committee is made up of workplace volunteers with management often offering incentives to the employees for their involvement and leadership. Nascent leadership is one of the benefits of a strong SCWE. The Moab Project employee safety committee has been a nucleus for budding leadership among the workforce. The committee has the choice to invite management or not. They have operated both ways, and, if desired, they pick and choose when and who they want to invite to their meetings. The interactions between committee members and management have always been viewed as positive. It is important that management act on the committee's recommendations in a timely manner. In the beginning, the committee demonstrated more patience than reasonable when their recommendations were not acted on quickly enough. Management realized this short coming and corrected this problem. This further empowered the committee members to take their roles seriously and employees outside the committee take notice, and they continue to give more suggestions to the committee members for management consideration.

Sustaining a strong working SCWE requires a plan. The Moab Project SCWE sustainability plan has three focus areas:

1) Leadership involvement;
2) Employee engagement;
3) Learning organization.

Each focus area is defined and associated attributes are aligned. Examples of attributes include demonstrated safety leadership, management engagement and time in the field, open communication and fostering an environment free from retribution, clear expectations and accountability, teamwork and mutual respect, credibility, trust and reporting errors and problems, performance monitoring through multiple means, and a questioning attitude.

For SCWE to take hold and work in a sustained manner, there is a dependence on employees believing that the organization supports continuous improvement and effective resolution of problems, while encouraging the sharing and utilization of operational experiences.

Recently, an outside DOE audit team assessed the Moab Project and concluded that the project had a healthy, functioning SCWE. Now the challenge is to sustain this progress.

ACKNOWLEDGEMENTS

Figure 1 is courtesy of J. Goeckner.

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AN OVERVIEW OF URANIUM MILLING PROCESSES, ASSOCIATED WASTES AND ATMOSPHERIC RELEASES[30]

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Abstract

This paper provides an overview of conventional uranium milling operations, extraction of uranium as a by-product from non-conventional resources, wastes generated from milling operations and airborne radioactive and chemical effluents within a wider scope of a high level document that primarily intended to provide non-exhaustive technical information.

1. INTRODUCTION

Before uranium ore can be extracted from a mine, a considerable amount of waste rock and below grade ore has to be removed to permit access to the economic grade ore. The ores are segregated on the basis of assay into waste rock and below grade ore as well as mill quality ore. The uranium ore is extracted from the mines and then transported to the mill where it is processed. Once at the mill, the ore is crushed and usually additionally ground, and treated with chemical solutions to dissolve the uranium, which is then recovered from the solution to produce a concentrate (sometimes called yellow cake) containing a high concentration of uranium. Tailings are the wastes from the millings processes and are stored in mill tailings impoundments, a specially designed waste disposal facility. Simplified flow chart of uranium ore processing from mining to the production uranium ore concentrate is shown in Fig. 1. Subsequent sections briefly describe conventional uranium milling processes followed by an illustrative flowsheet example, extraction from non-conventional resources, wastes generated and potential environmental impacts.

2. CRUSHING AND GRINDING

The initial step in conventional uranium ore milling involves crushing and usually grinding operations to produce a sized ore suitable for acid or alkaline leaching (heap leaching requires crushing only). The feed preparation requirements are nearly always specific to the site. Grinding in a mill can be wet or dry. The advantage of wet grinding process is that the dust and radiation hazards associated are essentially eliminated. The primary objective of crushing and grinding in the vast majority of uranium milling operations is to liberate the gangue minerals that are intimately associated with uranium deposits to a degree required for effective leaching i.e. expose the surfaces of uranium minerals to the leaching chemicals.

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[30] Presented at the Third Consultancy Meeting for the preparation of an IAEA publication on the Major Environmental Considerations Associated with Uranium Mining and Milling, 23–27 March 2015, Vienna.

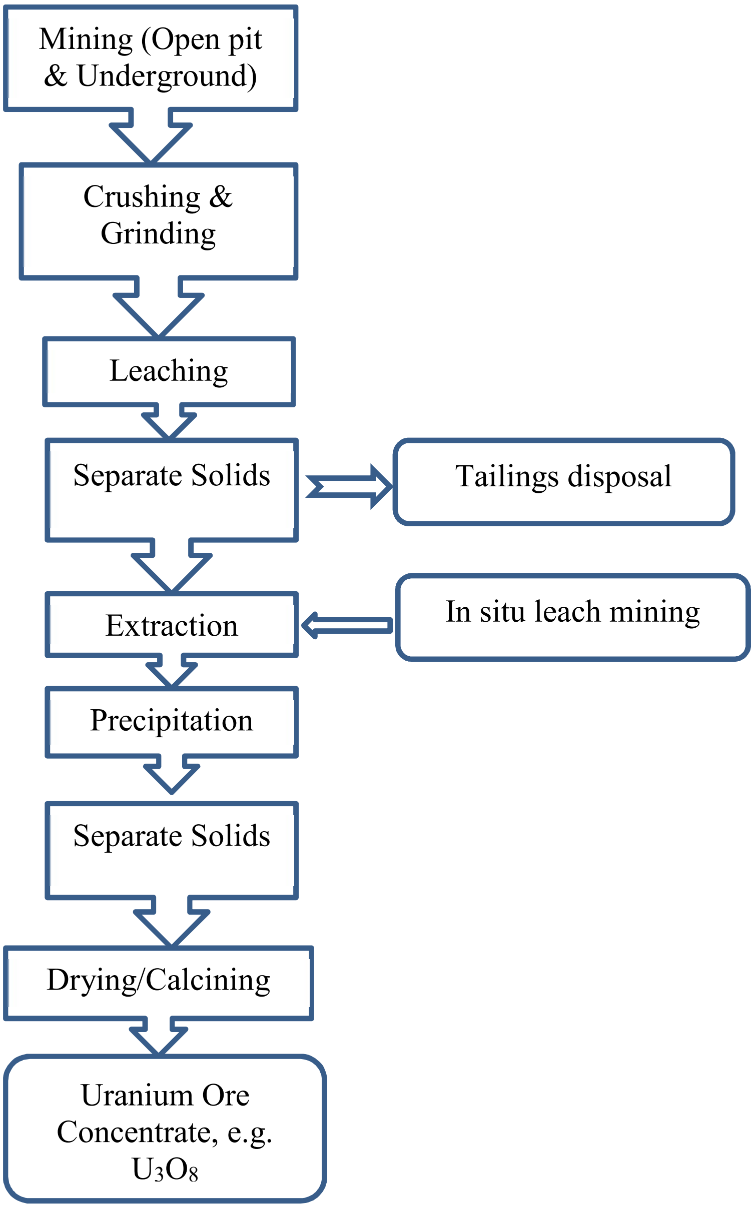

FIG. 1. Simplified flow chart of conventional uranium milling.

The degree of grinding required to achieve this objective for different ores may vary considerably depending upon the type and mineralogy of the ore body being processed (sandstone, limestone, gneiss, etc.), leaching type and lixiviant used (acid or alkaline). It is rarely necessary to fracture the grains of a sandstone ore because the uranium occurs primarily in the cementing material between the grains. Other ores, in particular those containing refractory minerals, may require the breakage of mineral grains themselves [1].

Crushing and grinding are significant energy consumers. Grind size will affect the usage of power and chemicals, and the characteristics of tailings. In general, the energy intensity of uranium production is inversely related to the grade of the ore. Lower grade ores are presumed to lead to increased mining and milling energy requirements per unit of product basis [2].

3. LEACHING

Uranium milling is based primarily on hydrometallurgical operations such as leaching, purification (solvent extraction and ion exchange) and precipitation. Leaching is an important step in the processing of a uranium ore where uranium is chemically leached from the ore crushed and ground to the required size or from slurry in the case of underground mining, in order to produce uranium ore concentrate with a uranium content of at least 65%. This material is normally termed *yellow cake*, despite the fact that not all modern forms are yellow.

Uranium ores are treated by either acid or alkaline reagents with sulphuric acid or sodium carbonate–sodium bicarbonate systems used almost exclusively for commercial uranium recovery. In general, alkaline leaching is milder and more selective than acid leaching and is used for the treatment of high carbonate ores, which would consume excessive amounts of acid. A general guide has been that if the ore contains more than 2% of carbonates then alkaline leaching is more economical, depending on the grade, but other factors must also be considered [3]. Such factors include the efficiency of uranium extraction, water usage (particularly in remote locations), energy consumption, product quality requirements and environmental considerations.

Although acid leaching is used in the majority of uranium mills, alkaline leaching can have some inherent advantages; these are: (i) the carbonate–bicarbonate solution is more specific for uranium minerals, leaving most of the associated gangue unattacked, which makes possible direct precipitation of uranium from the leach solution without need for further purification; and (ii) the carbonate solution can easily be regenerated. These characteristics also lead to a number of disadvantages that include the following [1, 4]:

a) Fine grinding is required to expose the uranium minerals;
b) Some gangue minerals such as calcium sulphate and pyrite, if present, can react with the alkaline reagent resulting in a high consumption;
c) The more refractory uranium minerals are not dissolved under alkaline conditions;
d) Elevated temperatures and/or pressures are sometimes required;
e) The kinetics (speed of reaction) is normally slower than acidic leach.

The selection of leaching reagent for dissolving uranium minerals is dependent in part on the physical characteristics of the ore such as: type of mineralization, ease of liberation and the nature of other constituent minerals present [5]. After selection of the reagent the next step is the choice of the leaching system. The following techniques are available.

a) Agitation leaching at atmospheric pressure (acid and alkaline);
b) Pressure leaching (acid and alkaline);
c) Strong acid pugging and curing (acid);
d) Heap leaching (acid or alkaline);
e) In situ leaching (mainly acidic except in the USA where alkaline is the norm).

Terms such as in situ leaching, in place leaching, heap leaching and percolation leaching have been used to denote various modifications of the static bed leaching practices where the ore bed remains static and the solutions are circulated through the stationary bed of ore. In the context of this discussion, the following definitions will be used [1]:

a) Heap leaching: The ore is mined and then piled in a collection system. Leach solutions are distributed over the upper surface of the heap and passed downwards through the bed of the ore. The bed may be run-of-mine ore (ROM) or coarse crushed material, although in modern practice agglomeration of the crushed ore is the norm;

b) Percolation (vat or tank) leaching: The mined ore is fine crushed (normally to about 25 mm size or less) and then bedded into tanks or vats. The leach solutions are passed through the static ore in either an upwards or a downwards direction;
c) In situ leaching: The ore is not moved from its geological setting. The leaching solutions are forced, usually in a horizontal direction, through the ore body and recovered by a series of wells;
d) In place leaching: The ore is broken by blasting but left in underground stopes. The leach solutions may pass through the static ore bed in a downward direction or the stope may be at least partially filled with the leaching solution. The leach solutions are recovered by a collection system below the bed of broken ore.

In situ leaching is at present limited in application to confined sandstone formations (high permeability) containing comparatively small deposits of low grade ore at a relatively shallow depth. However, it can offer significant economic advantages as the wellfield replaces the mining and crushing operations and leaching equipment associated with conventional processing. Its disadvantages are the relatively low recovery and sometimes stringent requirements to restore the mined area to acceptable conditions [6].

Heap leaching may suffer from poor recovery, without offering the cost savings associated with in situ leaching. The ore must be mined, transported and sometimes crushed before being leached. The preparation of an impervious base is usually required. Improvements in extraction efficiency require innovations such as pelletizing and the provision of leach vats. Where low grade ore is involved, the more modest capital and operating requirements of a heap leaching operation may give it an economic advantage over conventional leaching routes; in particular where bacterial action and in situ sulphide minerals can be used to provide a degree of autolixiviation (i.e. bacterial oxidation of sulphide produces ferric sulphate and sulphuric acid lixiviant capable of leaching uranium). Heap leaching may be attractive for processing below ore grade uranium material (bogum) stockpiled during mining operations. However, bogum is often weathered and too fine for a heap leaching operation without pelletizing or agglomeration, or treatment to remove fines [6, 7].

There is an increasing trend towards optimization of uranium recovery process. Optimization is occurring in several ways, one of which is balancing energy usage and chemical consumption against recovery through increasing application of the heap leach process. Lagoa Real in Brazil is one of the world's newer uranium processing facility and treats all ore by heap leaching. Technology transfer from the gold industry, where heap leaching accounts for a substantial percentage of production, has contributed in shifting production focus in uranium industry from conventional milling to heap and in situ leaching in several countries [8].

For mines where ore is physically removed for treatment, the choice between leaching systems (e.g. agitation leaching at atmospheric pressure, pressure leaching, strong acid pugging and curing), is mainly determined by the mineralogy of the uranium and the gangue. Agitation leaching at atmospheric pressure is most commonly used, with pressure leaching employed for refractory uranium minerals and alkaline conditions where the rate of reaction is too slow under conventional conditions.

Pressure acid leaching has been adopted for a few uranium operations treating more refractory ores, especially in the presence of sulphides such as pyrite which can oxidized to form the sulphuric acid and ferric iron required for the process. Pressure alkaline leaching was introduced to treat more refractory high acid consuming ores and was successfully used at a number of operations.

Bio-leaching has also been applied commercially for pyritic heap leaching operations and for in place leaching of low grade underground mine stopes broken by blasting and to old mine stopes. Since the last uranium boom there have been major advances in the application of both heap bio-leaching of run-of-mine ore (ROM) or crushed ore and agitated tank bio-leaching of concentrates, such as the use of aeration pipes, addition of nutrients, development of more efficient agitators and the development of new ultrafine grinding equipment. This is likely to lead to a greater use of bio-leaching in future uranium projects involving sulphidic ores. Heap or in place systems will be more suitable for lower grade ores, while tank bio-leaching will be more applicable to uranium bearing sulphidic concentrates [7].

Strong acid pugging is generally used for treating refractory ores. Reaction times and acid consumption in this type of process are generally less than in conventional acid leaching and higher extractions from quite refractory ores can be obtained using an ore that is much coarser than is required with conventional processes. The ability to use a coarser ore not only reduces the grinding costs but also makes subsequent separation of the pregnant leach solution from the leach residue easier. This technique is also advantageous for ores where normal agitation leaching results in the rapid breakdown and dispersion of clays and the dissolution of large quantities of silica [1].

In a few cases, uranium ores may undergo roasting to increase the solubility of valuable constituents and to improve the physical characteristics of the ore. As example, ores are roasted to enhance vanadium extraction, to improve the ore settling and filtration characteristics by alteration of clay minerals in the ore and to remove organic carbon which can cause problems in the leaching circuits [1].

Leaching is the main chemical reagent consumer in the milling process. In addition to dissolving uranium, leaching mobilizes a range of potential contaminants, apart from radionuclides. Reagent quantity can be minimized by optimization of leach conditions to minimize dissolution of gangue minerals and leaching at higher slurry density so the amount of acid needed to maintain free acidity is reduced [9].

In uranium leach processes employing sulphuric acid as the lixiviant, only a relatively small quantity of acid is gainfully employed in extracting uranium from the host ore. The remainder of the acid is consumed by the gangue constituent elements. Many new projects that are being considered today have gangue acid consumptions in excess of 95%. In contrast, alkaline leach processes do not experience the same high reagent consumption rates as acid processes. The solubility of many of the impurity elements in uranium ores (such as Fe, Mg, and Al) in the alkaline leach is quite low. However, the alkaline operations do encounter some challenges with gangue element solubility [10].

3.1. Acid leaching

In nature uranium occurs in the tetravalent form, the oxide of which is UO_2, and the hexavalent form, the oxide of which is UO_3. In its hexavalent form uranium goes directly into solution. Tetravalent uranium has a low solubility in both dilute acid and carbonate (alkali) solutions. To achieve economic recovery of uranium in the tetravalent state, oxidation to the hexavalent state is essential. It is therefore important to maintain proper oxidizing conditions during leaching of these minerals to achieve high uranium extraction [6, 11]. Various oxidants have historically been used and are currently employed to oxidize tetravalent uranium to hexavalent uranium in acid and alkaline leaching of uranium ores, these include:

a) Manganese dioxide (MnO_2) as milled pyrolusite;
b) Sodium chlorate ($NaClO_3$);
c) Hydrogen peroxide (addition as H_2O_2 or Caro's acid (H_2SO_5));
d) Ferric iron;
e) Oxygen in pressure leach circuits;
f) Sulphur dioxide/air (oxygen) mixture.

Currently sulphuric acid is almost exclusively used for acid leaching, typically combining high leach performance and relatively low cost. Considering its chemical properties, nitric acid is the most capable leaching agent for uranium. Unlike sulphuric acid it has a high oxidation potential and does not generate an insoluble residue (e.g. gypsum). Nevertheless, its high cost and ability to dissolve many associated gangue minerals greatly reduces the utility of nitric acid in uranium leaching practice. Hydrochloric acid (HCl) solution is intermediate between nitric and sulphuric acid, when cost and the intensity of reaction with uranium ore are considered. Hydrochloric acid does not produce insoluble compounds which plug the porosity. It is, however, much more corrosive to metal and equipment [6, 12].

Ferric iron (Fe^{3+}) acts as the principal oxidant of tetravalent uranium in acid leaching. However, other oxidants namely, pyrolusite (manganese dioxide), sodium chlorate and Caro's acid (a specific mixture of sulphuric acid and hydrogen peroxide) are typically used to assist in oxidation. Pyrolusite consumes more acid and the product from the oxidation reaction, Mn^{2+}, has a potential environmental impact. On the other hand, Caro's acid offers significant environmental advantages in that the residual reaction product is water [9, 11].

Uranium ores containing sulphidic minerals can be leached in the presence of oxygen only at elevated temperature and pressure. This technique is widely known as pressure leaching. These sulphides are converted to sulphuric acid and ferrous sulphate at elevated oxygen pressures. The ferrous sulphate is subsequently oxidized to ferric sulphate, which is an effective oxidant for the dissolution of tetravalent uranium.

3.2. Alkaline leaching

As indicated earlier, alkaline leaching of uranium ores is usually a viable alternative to acid leaching if: (a) the ore contains significant amounts of acid consumers such as carbonates; (b) uranium mineralization is in the hexavalent form or if it can be readily oxidized. Unlike acid medium in which the rapid oxidation of tetravalent uranium is achieved by the presence of ferric ions in solution, ferric ions cannot be maintained in alkaline carbonate solutions. The lack of such a catalyst that is largely responsible for the very different conditions required in carbonate leaching as compared with acid leaching. Carbonate leaching calls for more severe conditions of pressure and temperature, usually from 70 to 80°C, often a longer leaching time, and a finer grind [1].

4. SOLID–LIQUID SEPARATION

Solid–liquid separations are one of the most important components of uranium processing operations. Not only can these operations represent up to 40% of the mill capital costs, but uranium losses due to incomplete washing can significantly reduce the operating profits. Nearly all mills used either thickening or continuous filtration for the liquid recovery and tailings separation steps. Thickening, as applied in uranium processing, can be defined as removing a portion of the liquid from a slurry by allowing the solids to settle under the influence of gravity in some form of sedimentation vessel, often with the addition of chemical flocculants/coagulants [1].

Solid–liquid separation and uranium recovery are typically achieved through a CCD (counter current decanting) washing circuit. This process is simple, flexible and effective but is unattractive in terms of minimizing environmental impact, as a CCD circuit has a large plant footprint and high water requirements, although progress is being made to reduce the footprint and decrease the water requirement. Alternatives to a CCD circuit include filtration and washing, Resin In Pulp (RIP) or Resin In Leach (RIL) [1, 9].

CCD circuits have generally been preferred to filtration on the grounds of ease of operation and reliability, even though filtration has the advantages of reducing water usage and increasing the uranium concentration of the pregnant liquor. The filtration option after leaching has the potential of producing a highly dewatered filter cake (20 to 25 wt% water) that can be used directly to produce paste tailings. However, advances in resins offers an RIP technology the possibility of improving the environmental performance of uranium extraction plants by improving uranium recovery, reducing water use and minimizing bleed liquor.

5. CONCENTRATION AND PURIFICATION OF THE LEACHING SOLUTIONS

Following the dissolution of uranium from the ore by the acid or alkaline leach process, the resulting impure and dilute solutions have to undergo concentration and purification as a prerequisite to the production of a final, high grade, uranium concentrate. Concentration and purification of the leaching solutions can be accomplished by ion exchange or solvent extraction depending upon the type of the feed solution. The variables include the concentration of the uranium, the amount and concentration of the impurities, and the desired final purity of the uranium product. The composition of the leaching solution will essentially be dependent upon the mineralogy of the ore and the leaching medium.

The ion exchange process is normally used for the treatment of both pulps and clarified solutions in either the acid or alkaline circuits. Strong and intermediate base anionic type resins are employed which preferentially adsorb the uranyl anionic complexes present in the solution excluding metallic cations, resulting in a high degree of purification.

The advent of solvent extraction and ion exchange represented important developments for both recovery and upgrading of dilute process streams. The uranium industry has been a leader in the development of ion exchange technology both to concentrate and purify leach solutions. A wide variety of both batch and continuous systems has been installed in uranium mills throughout the world.

Solvent extraction (often abbreviated to SX) is a separation, purification and recovery technology based on the differing solubilities of compounds in two different immiscible liquids, usually water and an organic solvent. Solvent extraction recovery of uranium can only be used in conjunction with clarified acid leach solutions. Carbonate leach recovery systems do not use solvent extraction as a recovery or purification stage because there are as yet no extractants capable of extracting uranium at a high pH and in the presence of a high salt content. Solvent extraction consists essentially of two steps: The first is 'extraction', where the uranium bearing leach solution is thoroughly mixed with an organic solvent mixture and the uranium is selectively transferred to the organic phase. The organic solvent mixture is made by dissolving an organic reagent, called the 'extractant', and a 'modifier' (optional) in a hydrocarbon-like solvent (diluent). The extractant forms a complex with uranium which has a high miscibility in the hydrocarbon phase. The second step, called 'stripping', consists of re-extracting the uranium from the organic phase into the aqueous phase. This is achieved by contacting the extract with an aqueous solution of a suitable reagent.

The oxidizing sulphuric acid leach is aggressive and non-selective resulting in the dissolution of many other elements apart from uranium. The most common soluble impurities include iron, amorphous silica, tungsten, aluminium, antimony, arsenic, molybdenum, vanadium and titanium. Chloride, phosphate and nitrate anions might also be present in the leach solution. Thus, an organic solvent is introduced to selectively extract the uranium species from the leach solution. In most conventional mills, uranium is recovered by solvent extraction using tertiary amines as modifiers to a kerosene-like solvent in mixer–settlers. The tertiary amines are selective for uranium in the presence of most impurities. The most significant potential environmental impact of solvent extraction is contamination of the aqueous process liquor by organics ([9].

The choice of an extractant and diluent are two important aspects of a successful solvent extraction operation. The properties of a usable diluent can be summarized as follows [13]:

a) It should have a high flash point and preferably a high boiling point;
b) It should have a low freezing point as well as low water solubility and a low chemical transformation rate with water, extractants and solute;
c) It should not form third phases during loading conditions.

Although the solvent is recycled, solvent loss occurs through evaporation, degradation, volatility and solubility as well as by entrainment in raffinate (the liquid stream which remains after extraction of uranium from the original leach solution) and crud (the stable emulsion that accumulates at the interface between organic and aqueous solutions); e.g. solvent losses in the process can have a major impact not only on the economics of the operation but also on the receiving environment owing to the discharge of process effluents from the solvent extraction circuit.

Loss of raffinate can be minimized by the use of standard techniques for organic liquid recovery (e.g. carbon column, flotation), but crud losses are essentially unavoidable and are a function of the amount of solids in the feed solution (liquor) and the design of the mixer/contactor. For high grade leach solutions, solvent extraction (or ion exchange) can be replaced by a direct precipitation system. This system has a similar ‘front end’ to solvent extraction, which includes grinding, leaching and filtration. The ‘back end’ includes a partial neutralization step in place of the solvent extraction circuit, where iron and other impurities, but not uranium, are selectively removed, followed by direct precipitation of the uranium using hydrogen peroxide [9].

6. PRECIPITATION AND DRYING/CALCINATION

The final step in the uranium milling process is to recover uranium as a high-grade oxide concentrate (‘yellow cake’) and, in some cases, calcination. Uranium can be precipitated from solution over a wide range of pH, depending upon the solution type and the precipitant used. A number of different precipitants have been effective, including hydrogen peroxide, ammonia, magnesia, magnesium hydroxide and sodium hydroxide. The type of precipitating reagent chosen is influenced by factors such as the purity of the feed solution, the product specifications demanded by buyers, the relative reagent cost and the possible environmental impact of the reagent.

In a conventional flowsheet, stripping is accomplished using ammonium sulphate, and uranium is precipitated with ammonia solution as ammonium diuranate (ADU). This has been accepted industry practice, although there is increasing pressure to limit release of ammonia to the environment, which may occur through co-disposal of ammonium sulphate bleed streams and tailings slurries. In some cases, uranium is precipitated as magnesium diuranate (MDU). Another option is the use of a strong acid strip/hydrogen peroxide precipitation process to produce uranyl peroxide. At some sites, for instance Key Lake in Canada, ammonia is being recovered from waste streams and sold as ammonium sulphate fertilizer [9].

In some cases, a uranium concentrate may be precipitated directly from a leach solution, without preconcentration and purification by solvent extraction or ion exchange. The use of alkaline leaching, if there are high acid consuming minerals present, will result in a more or less selective dissolution of uranium with very little solubilization of the gangue. Such a leaching solution may be treated by direct precipitation for the recovery of uranium. Solutions from the acid leach process invariably contain many impurities such as aluminium, iron, manganese, titanium, vanadium, copper, nickel and silica; hence any direct precipitation technique would normally lead to an impure product.

Ammonium diuranate (ADU) or magnesium diuranate (MDU) calcines at ~ 800 °C into a multi-hearth calciner, yielding a product which typically contains ~99% U_3O_8 at a pH value of 7.2. Uranium oxide concentrate (U_3O_8) can also be produced from uranyl peroxide using a strong acid strip/hydrogen peroxide precipitation. The advantage with this method is that the peroxide requires ‘drying’ at a much lower temperature, typically 250 °C. This operation has a much lower solids discharge to the stack than a multi-hearth calciner. The energy requirement for low temperature drying is significantly less than that required for calcination by 40% to 50% [1, 9].

7. URANIUM EXTRACTION AS A BY-PRODUCT

In addition to the conventional milling operations, uranium can also be obtained as a by-product from a number of unconventional resources. These resources include potentially recoverable uranium associated with phosphates, non-ferrous ores, carbonatite, black schist, porphyry copper, gold, seawater, mineral sands and coal–lignite, resources from which uranium is only recoverable as a minor by-product. Very few countries currently report unconventional resources. Most of the unconventional uranium resources reported is associated with uranium in phosphate rocks, gold and copper [14].

Phosphate rocks are prime sources of phosphate fertilizers and phosphoric acid with concentrations of uranium as by products. Most natural phosphates contain between several tens and several hundreds of parts per million of uranium. A high percentage of the uranium in commercial phosphate rock is present as an intrinsic component of the apatite mineral lattice. When the phosphate rock is processed to produce phosphoric acid by the 'wet process' method (i.e. digestion of phosphate rock with sulphuric acid), most of the uranium is taken into solution. The uranium obtained from phosphoric acid remains an important potential source. As phosphoric acid is the marketable product and uranium only a by-product, the recovery of uranium should not adversely affect the quality of the phosphoric acid. Solvent extraction is currently considered as the most highly proven and economic method of extracting uranium from phosphoric acid [15].

Uranium commonly occurs with copper and sometimes gold resulting in a modified milling process. Where uranium dominates the ore, copper will remain in the aqueous solution at the solvent extraction stage and then be recovered from that. Where copper dominates the ore in the form of sulphides, preliminary separation by floatation techniques may be carried out after grinding. Agitation and aeration causes copper-bearing sulphide particles to attach themselves to air bubbles and float. The underflow contains the bulk of the uranium and can then be leached with sulphuric acid and an oxidizing agent, and then separated with solvent extraction methods, much as in a normal uranium mill [8, 12].

Uranium also occurs in rare earth element deposits and in heavy mineral sands deposits where it contained in the mineral monazite. In each case separation of uranium requires unconventional processes. Uranium can also be directly adsorbed onto organic material in lignite, black shale, clay and sandstone immediately adjacent to lignite, as opposed to forming discrete uranium minerals. Extraction from the carbonaceous matter is by uranium oxidation or roasting and high reagent consumption [16].

8. WASTES FROM MILLING OPERATIONS

The waste products from the conventional milling process are known as tailings (not to be confused with uranium tails, the depleted product from the uranium enrichment process). The tailing slurry is considered the most significant waste from the milling process. This waste stream is a mixture of leached solid ore and waste solutions from the grinding, leaching, uranium purification, precipitation and washing circuits of the mill. Because uranium makes up only a small part of the ore, the tailings are essentially of the same volume as ore fed to mill. Tailings are pumped from the plant as slurry and returned underground, back to the mined-out pit or, in some cases, deposited in specially engineered tailings dams. The tailings also contain any heavy metals originally present in the ore. Therefore, if provision is not made to completely contain the material, the tailings may be a long term source of these substances which may enter the groundwater below the impoundment [17, 18].

Liquid waste from milling operations and runoff from the mine stockpiles are collected in secure retention ponds. These can be lined with clay as uranium in solution can pass through sand but adheres to negatively charged clay particles. Heavy metals and other contaminants may be isolated and recovered and the liquid portion is either recirculated back to the mill or naturally evaporated away. For example, the McLean Lake operation uses barium chloride, lime and ferric sulphate to precipitate arsenic and radium, neutralize acidic waste and prepare the tailings for disposal in the tailings management facility [19]. For more details on tailings management, the reader is referred to the case studies highlighted in the IAEA [20].

The impacts on the environment from uranium mining and milling residues are not all related to the radionuclide content alone. The nature of the processes used in the milling may results in increased availability of a wide range of heavy metals in the tailings, or the residues of process reagents such as sulphate, ammonia, chloride, pyrite, kerosene and sulphuric acid may have the potential to cause adverse environmental impact [21].

The presence of non-radiological contaminants can exacerbate the availability of the radionuclides to the environment. In this regard, the potential for uranium mining and milling residues to cause environmental harm is little different from that of other forms of mining, and the resultant impacts may be quite similar. Indeed, it is not adequate to consider the radiological risk only. The other effects may include [22]:

a) The chemical toxicity of the radionuclides, including uranium;
b) The chemical toxicity of heavy metals and metallic compounds;
c) The chemical toxicity of non-metallic minerals and compounds in the ore or introduced during processing (e.g. sulphuric acid, kerosene);
d) Acidity, resulting from sulphidic (ore) minerals or acid introduced during milling;
e) Increased turbidity in surface waters;
f) Increased salinity.

The types of non-radiological contaminants that may cause harm are dependent on the mineralization in the ore body, the gangue mineralogy, the overburden mineralogy and the processing technique used in the mill. Elevated acidity plays a major role in increasing the mobility of heavy metals in aqueous solution, including uranium, as well as copper, arsenic, cadmium and other metals. The transport of chemical residues from mill tailings into the environment through aquatic or atmospheric dispersion needs to be controlled and kept to the absolute minimum achievable using best practicable technology and 'as low as reasonably achievable' principle (ALARA). Other processes that might act on uranium mill tailings to produce hazardous conditions are climate, biological processes and chemico-mineralogical changes. Furthermore, many of the contaminants, especially the heavy metals, retain the same levels of toxicity permanently, unlike the radionuclides which gradually decay and become less dangerous with time [21].

8.1. Atmospheric releases

The processing of uranium ore in concentrating mills generates wastes and effluents that are both radioactive and nonradioactive. Solid, liquid and gaseous effluents are released to the environment. The atmospheric releases from uranium mining are, for the most part, similar to releases from conventional mines. They are, in addition to typical releases, radon and radon progeny, and radioactively contaminated dusts [17].

8.2. Airborne chemical contaminants

Airborne chemical (nonradioactive) contaminants released to the environment during uranium milling operations include fuel combustion products (oxides of carbon, nitrogen and sulphur) from process steam boilers, and power generation, sulphuric acid fumes in small concentrations from the leach tanks vent systems, and vaporised organic reagents, mostly kerosene, from the solvent extraction ventilation system. In addition, where sulphuric acid is produced on site, sulphur dioxide is exhausted to the atmosphere if no desulphurisation equipment is installed [17].

8.3. Radioactive airborne effluents

Radioactive airborne effluents from milling include dust and radon gas released into the air from ore stockpiles, crushing and grinding of ore, drying and packing of yellowcake, and from the tailings retention system. The amount of dust produced in the processing operations is reduced by ventilation extract scrubbers and/or filters. Short lived radon progeny, resulting from the decay of radon, are a major source of radiation exposure for uranium mine workers, particularly in underground mines. Ventilation is used in underground mines to remove radon and thereby limit the exposure to its progeny. However, the expelling of the radon and its progeny from underground mines results in dispersal of these radionuclides into the environment. At in situ leach (ISL) mines radon gas is dissolved in the uranium bearing solution that is pumped from the ore body. This radon may be released if the solution is exposed to the environment in tanks or ponds [17].

The tailings contain nearly all of the naturally occurring radioactive progeny from the decay of uranium, notably thorium–230 and radium–226. The presence of radium–226 provides a long term source of radon. As radium decays, radon gas is formed. During the life of the mine, the tailings are generally covered by water to reduce surface radioactivity and radon gas emission. On completion of the mining project, it is normal for the tailings to be covered with at about two metres of clay and topsoil. This reduces the surface radiation to levels normal for the region and allows vegetation to cover the area.

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EXTRACTION OF HAZARDOUS CONSTITUENTS FROM TAILINGS RESULTING FROM PROCESSING OF HIGH GRADE URANIUM ORE[31]

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Abstract

Conventional production of uranium across the world creates millions of tonnes of tailings annually, which are typically placed in above ground tailings impoundments. However, particularly tailings resulting from leaching of high grade uranium ores have the potential to cause serious environmental impacts. In spite of significant improvements which have been made in recent years to operational and short term safety of those tailings impoundments, their provision of reliable long term safety is still not satisfying. By advancement of the processing technology for uranium ore a solution is achieved to comprehensively eliminate risks which can derive from those tailings. Removal of radionuclides other than uranium as well as toxic metals can be achieved, if also these are intentionally extracted. The overall objective is to prevent the generation of future uranium production legacies with associated high follow–up costs.

1. BACKGROUND

The surficial disposal of tailings in engineered impoundments has been considered to be generally a reasonable solution. By relatively moderate effort a disposal opportunity has been provided, which apparently has been meeting operational requirements.

Conventional above ground tailings impoundments, however, can also comprise disadvantages. If properly engineered, such facilities are able to cope with challenges like dam failure or seepage generation during operation and in the short term (e.g. up to some centuries). However, it is potentially a fundamental disadvantage of conventional tailings impoundments that long term safety and integrity, which from a radiological point of view can be necessary up to several tens of thousands of years, may be provided insufficiently.

Provided that maintenance and monitoring measures are ensured, conventional tailings impoundments can provide integrity maximum for a timespan of up to 1000 years [1]. Their integrity duration can be even much shorter in case of high georisks (like earthquakes, floods etc.). Furthermore, in many countries institutional control is assumed to be reliable not longer than 300 years [2].

Consequently, the disposal of tailings resulting from conventional processing (e.g. of high grade uranium ore in above ground tailings impoundments) appears to be a temporary rather than a true long term solution to their containment.

2. JUSTIFICATION

Of particular concern for the long term safety of applicable tailings impoundments is that long-lived daughter nuclides of uranium are conventionally disposed of with tailings. The contained radioactivity is predominantly caused by radium (mainly Ra–226) and its daughter nuclides like

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[31] Paper first presented at the Technical Meeting of the UMREG in Bad Schlema, Germany, August–September 2015.

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radon (Rn–222) as well as by thorium (mainly Th–230[33]). Approximately 85 % of the original activity remains in conventional tailings [3]. Almost 65 % of the original Ra–226 mass will still remain even after the maximum envisaged lifetime of tailings impoundments (1000 years, as mentioned).

Typically, the low-level activity tailings resulting from uranium production fulfil criteria for classification as Technologically Enhanced Naturally Occurring Radioactive Material waste. Moreover, conventional tailings resulting from processing uranium ore yet with a grade > 0.3% need to be classified as long lived radioactive waste[34]. To cope with this significant content of long-living radionuclides the IAEA recommends at first consideration of underground disposal of tailings, while acknowledging that "the use of engineered surface impoundments may be the only viable option and should be [also] considered" [5].

Above ground disposal of tailings has been in use mainly due to the huge volumes of tailings involved [6]. The historical acceptance of above ground tailings disposal does not mean that the usual approach is recommendable, just that it is understandable. Whereas long lived radioactive waste generated in nuclear energy generation (even long lived radioactive waste of much lower activity than e.g. spent nuclear fuel) is generally intended to be disposed of in underground repositories, a similar approach so far becomes not apparent in uranium mining, raising the impression that different safety levels may be applied. However, tailings exist in much greater quantities and while the measures to manage them properly are different to those involved in nuclear energy waste, the same objective of acceptable risk should be applied.

The radiological long term safe disposal of eligible tailings would be enhanced if both radium and thorium were to be extracted and removed. The extraction of non-radioactive hazardous constituents such as the so-called heavy metals and other toxic elements would also enhance the safe disposal of tailings. Hazardous constituents contained in tailings could spread out into the environment should tailings impoundments lose integrity. To prevent this in the long term, ongoing maintenance of conventional tailings impoundments can become necessary to maintain their integrity with time. However, such approach may not be cost effective, because of potentially large and ongoing follow-up costs.

Therefore, advanced processing appears to be justified in following cases:

- In cases of high georisks of tailings impoundment failure due to earthquakes, floods and other natural causes;
- Where tailings are poorly stored in densely populated areas;
- Where higher grades of the uranium ore are involved;
- Where there are high concentrations of non–radioactive toxic elements.

However, a precondition is that the concentration of hazardous constituents and the risk of their release causing significant harm is high enough to warrant the effort and expenditure. The extraction and removal of trace amounts of radioactive or other contaminants might be neither technically feasible nor justified.

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[33] To simplify calculations it is assumed that all radium- and thorium-isotopes are generated by decay of U–238.

[34] If radioactive waste comprises long-living radionuclides (i.e. radionuclides with a half-lifetime above that of Cs-137) in such an amount that the average α-activity of long-living radionuclides is ≥ 400 Bq/g, final disposal in the underground is required [2, 4]. Note that there may be countries, where this usual limit is not in force.

Therefore, advanced processing appears particularly indicated in cases, which require increased safety measures like high grade uranium ore[35], which, if conventionally processed, result in tailings rich in radioactive daughter nuclides of uranium and pose an increased risk.

As the conventional way of above ground tailings disposal has been appearing to be questionable, yet almost 2 decades ago the proposed (but not realized) Jabiluka uranium mine in the Northern Territory of Australia has aimed to take another approach. After dewatering and mixing generated tailings with cement to a paste optionally it was planned to dispose them of into a number of constructed underground silos, which had their tops about 100 m below the ground [7, 8]. Though this approach for tailings management was in a technical view quite progressive at this time, the extraction and removal of hazardous constituents proposed here could provide an even more efficient alternative than underground disposal of conventionally processed tailings.

Such attempts to stabilize tailings [9], e.g. by mixing with cement, are not helpful in the end, because these measures concentrate on encountering challenges already in place in the short term like rainwater ingression, leakage of contaminants and similar. They do not reduce the overall inherent hazard of the still contaminant-bearing tailings and may not encounter long term challenges such as the release of contaminants by erosion of tailings impoundments with time. Nonetheless, stabilization can be helpful in some cases, particularly if concentrations of contaminants in tailings are too low concentrated to be economically extracted or where risks are low.

Even natural diagenesis processes in tailings, though assumingly leading to geochemical stability [10] as well as to some degree of consolidation, are not reliably able to encounter erosion forces. If particular circumstances favour this, with time natural attenuation processes in tailings impoundments may take place [11]. These might result in hardpan formation and self–sealing of conventional tailings impoundments. However, even if they occur, it is not possible to rely on these diffusion-controlled processes to prevent formation of acid mine drainage (AMD), because they may take dozens of years to develop and are often incomplete.

2.1. Radium

During leaching of uranium ore by sulphuric acid or alkaline agents just 1–5% of its original Ra–226 content becomes dissolved. Widely applied in uranium production facilities today, removal of dissolved Ra–226 from the process water is addressed by dosing of barium chloride [12, 13]. The efficiency of such treatment, however, is limited, because just liquid effluents of the conventional leaching process and certain affected water seepages are treated, not the solids from which the radium comes. In effect just the mentioned relatively small portion of dissolved radium is precipitated to meet relevant discharge requirements. Moreover, after precipitation this radium is typically again mixed with the conventional tailings, which thus contain almost all the radium of the original uranium ore.

The main portion of Ra–226, which predominantly remains in the solid fraction [14, 15] cannot be removed by $BaCl_2$ treatment and, thus, is always disposed of with the tailings. By disposal of this remaining portion of radium (and where applicable the precipitated radium from water

[35] The term “high grade uranium ore” appears, however, to be not exactly defined. AREVA already defines ores with a uranium content > 0.10% to be of high grade (note: world average grade of mined uranium ore is about 0.2 %), though Canada has deposits with a uranium content of up to 20%.

treatment, see above) in the course of tailings disposal, fundamental long term risks originate. These could be prevented if the whole Ra–226 content originally present in uranium ore first becomes mobilized using an appropriate extracting agent. Subsequently, radium removal can be performed comprehensively, for disposal separately to tailings.

Having a half–life of 1602 years Ra–226 has to be considered as the most critical radionuclide in tailings from conventional uranium ore processing. Decay of Ra–226 produces short–living daughter nuclides like radon (Rn–222). Radon gas and other daughter nuclides cannot be generated anymore, if Ra–226 is removed (Fig. 1). The parent nuclides of Ra–226 are of much lower radiological significance here, because they have either much shorter or much longer half-lives[36].

2.2. Thorium

Differing amounts of thorium become dissolved by conventional leaching of uranium ore with H_2SO_4 (between 30–90 %, while under alkaline conditions thorium appears to be much more insoluble and mainly remains in the tailings [14]). After separation of uranium from the leaching solution dissolved thorium nowadays is precipitated in order to meet discharge requirements by adjusting the pH (usually with lime milk). As with radium the precipitates rich in thorium are finally mixed with the resulting tailings. In the end conventional tailings contain almost all thorium originally present in the uranium ore.

Though a large step forward is taken by the proposed radium removal, it is advisable to extract and remove thorium as well, as it was shown radium and thorium together are responsible for over 90 % of the effective dose rate besides tailings impoundments. Otherwise decay of Th–230 leads to regeneration of its daughter nuclide Ra–226 and after 10,000 years about 10% Ra–226 would be generated again, compared to the original Ra–226 content.

Looking at the evolution of the effective dose (Fig. 1) it is obvious that the necessary level of safety, which can be ensured by the removal of radium and thorium, could only be achieved by integrity of conventional tailing impoundments of more than ~20,000 years.

2.3. Non-radioactive hazardous constituents

Conventional uranium ore tailings can contain, in addition to radioactive daughter nuclides, differing amounts of non-radioactive constituents (e.g. arsenic and the so-called heavy metals). By conventional water treatment these non–radioactive constituents are usually co-extracted from the process solution. Subsequently, the precipitates are then co-disposed of together with the actual tailings. However, in the course of extraction of radium and of thorium from uranium tailings these non–radioactive constituents can be mobilized and removed as well.

3. TECHNOLOGICAL OPPORTUNITIES

Generally, by another leaching chemistry – instead of or in addition (subsequently) to sulphuric acid or alkaline agents – extraction of the hazardous constituents present in uranium ore can be achieved.

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[36] It should be noted that certain radionuclides can additionally pose a chemotoxic hazard.

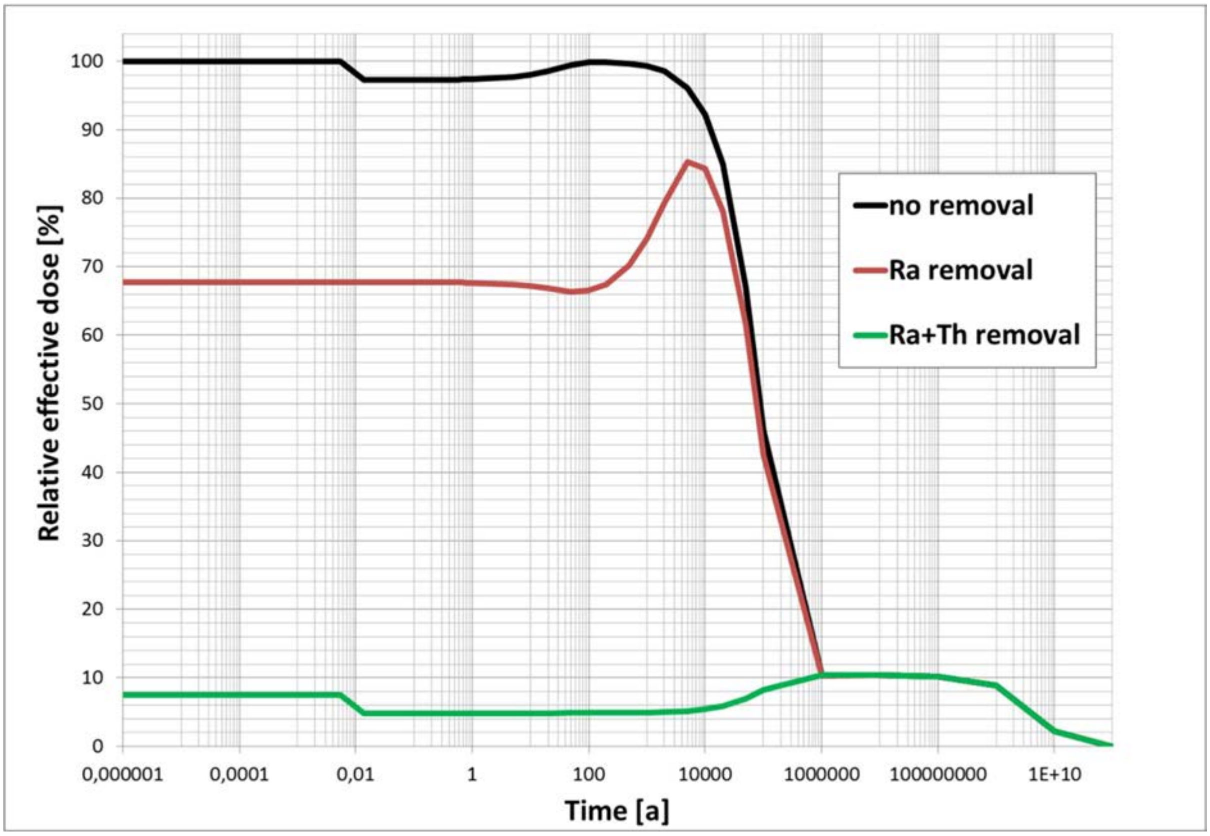

FIG. 1. Modelled reduction of the effective dose rate directly besides a tailings impoundment in case of no removal, removal just of radium and removal both of radium and thorium (inhalation pathway). Calculations are based on [16].

Various extraction agents for uranium processing were tested in the past. As leaching of uranium ore by sulphuric acid or alkaline agents provides generally the highest operational efficiency and cost effectiveness, these latter technologies became widely applied.

In addition, uranium production today is expected to meet the highest environmental standards. It has to be managed in an environmentally safe and long term reliable manner.

3.1. Operational uranium milling

In addition to efficient uranium extraction (typically about 85–95 % of the original ore content can be won today), the objective of advanced processing is also the efficient extraction of hazardous constituents.

The hazardous constituents can become available for removal by continuing the processing of uranium ore also to extraction from uranium tailings. In effect, such processed tailings would be virtually harmless and their disposal in above ground tailings impoundments will not give reason for concern. To achieve this, two general approaches appear feasible.

3.1.1. Extracting constituents in one step

By use of a a non–specific agent such as HCl [14] all constituents of interest can be extracted in one step (historical attempts made use of HNO_3 [17] and other agents). However, if tailings are aggressively leached in such a way, many constituents could come into solution (e.g. iron, aluminium and other common mineral constituents as well as major ions like calcium, magnesium and others). Thus, the extraction might need to be more specifically targeted.

By use of specific (selective) ion exchange resins precipitation and capture of harmful constituents from the 'pregnant' leaching solution could be achieved. At an existing uranium extraction plant, an almost complete replacement of existing (conventional) processing lines could be required to extract all constituents at once. Therefore, this solution would be more applicable for new, purpose-built uranium production plants.

3.1.2. Stepwise extraction (complementing existing processing lines)

Stepwise extraction of tailings after uranium extraction and before disposal appears to be preferable in most cases. This could be realized by integrating a new module between existing components that is immediately after conventional solid–liquid separation, which separates the pregnant leaching solution from the remaining tailings. The advanced processing module receives the conventional tailings as input for further treatment.

By stepwise dosing of reagents with different (specific) extraction capacity in adequate extraction reactors the different hazardous constituents become dissolved sequentially. If a general aggressive leach is not conducted, the leaching of each targeted element can be optimized. A possible technical solution is outlined in Fig. 2.

The liquid phase or phases, which then contains specific hazardous constituent(s) in dissolved form, is separated from the solid (tailings) phase by means of a solid–liquid separation (e.g. by a filter press). Subsequently, the dissolved hazardous constituent(s) in the liquid phase separated in this way is (are) precipitated by dosing of another capable reagent in a precipitation reactor and finally filtered for removal.

With regard to the effort for handling and disposal of extracted radium two general options for separation are given. The choice between these would need to balance financial and technical effort.

3.1.3. Precipitation of the extracted radium by dosing of $BaCl_2$

Since much sulphate is still present from previous leaching of the uranium ore by H_2SO_4, the extracted radium can be precipitated as a $Ba(Ra)SO_4$ sludge. Though the activity of this sludge would be presumably not very high (i.e. not very demanding), in the end its relatively large volume might lead to higher total disposal costs.

3.1.4. Precipitation of the extracted radium by membrane technology

By deploying membrane technology, the extracted radium can be precipitated in a more concentrated form (as well as, potentially, allowing even lower concentrations of radium to be extracted). In comparison to the sludge of the above option this concentrate would be of higher activity (requiring higher radiation protection effort), but due to lower volume might lead to lower total disposal costs. A similar decision as with radium needs to be made on precipitation of dissolved thorium — regardless of how it became dissolved (if by the conventional extraction of uranium ore or by the proposed extraction of tailings).

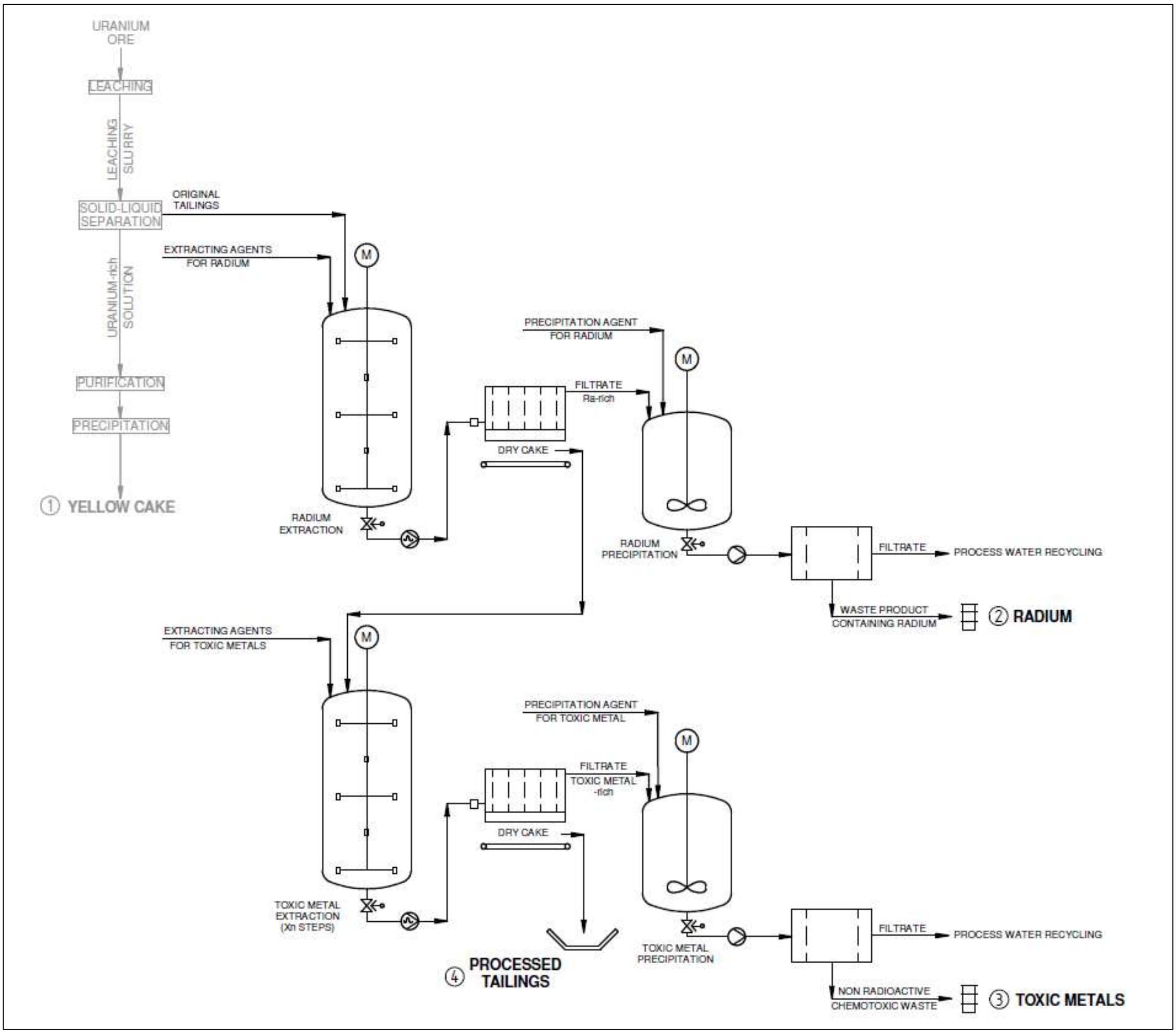

FIG. 2. Simplified process flow diagram of a technical solution for advanced uranium ore processing (extraction/removal steps shown just for radium and for toxic metals).

As mentioned above, dissolved thorium is precipitated by pH adjustment in the course of process water treatment today. In order to prevent the conventional disposal of thorium together with the tailings, those precipitates need to be collected separately also for disposal as long-living radioactive waste. However, presumably other dissolved species like so-called heavy metals co-precipitate together with thorium leading to an increased volume of waste of comparatively low activity. Alternatively, dissolved thorium can be precipitated (e.g. by using specific sorbents or also by membrane technology) which enable to separate in a more concentrated form.

In further sequences the remaining solid tailings are again treated by other extraction reagents for dissolution of further specific hazardous constituents, as required. The composition of the tailings to be processed as well as the selectivity needed dictate type and number of sequential extraction steps.

Compared to conventional processing (only two main fractions: yellow cake and tailings) by advanced processing uranium ore is split in up to five fractions:

a) Uranium (won as yellow cake by the original process);
b) Radium (contained in long-living radioactive waste to be forwarded to responsible authorities for underground disposal);
c) Thorium (long-living radioactive waste to be forwarded to responsible authorities for underground disposal, or storage for possible future reuse as a nuclear fuel);
d) Non-radiologic hazardous constituents (conventional waste to be disposed of, e.g. in hazardous waste landfills);
e) Processed tailings (now virtually harmless, thus disposable in landfill/simplified tailings disposal facilities).

In order to increase the efficiency of the indicated disposal ways it is essential to achieve a high degree of separation between the different constituents as well as to increase the purity of resulting fractions.

Many countries need to make arrangements for underground disposal of radioactive waste anyway. No doubt that handling and disposal of radium and thorium as long-living radioactive waste will be demanding (e.g. occupational radiation protection, pressure buildup in waste containers due to generation of Rn–222 by decay of Ra–226, etc.). Radium and thorium are both α emitters and can be high level- (radium) or low-/intermediate level waste (thorium), respectively. However, managing these waste types is feasible, including specific radiation protection needs, and the volumes are small compared to those of tailings.

By variation of process details generally every realization needs to contribute to specific conditions of each uranium deposit. Even if a particular technology works well for one type of tailings, there is no guarantee that it will work in the same way elsewhere due to site specific particularities like chemical/mineralogical composition, grain size, etc. Also, there might be the necessity to adjust process details even during treatment, because the tailings specifics resulting from the same deposit might change with time.

3.2. Remediation of legacy tailings impoundments

For reprocessing of legacy tailings in the course of remediation, similar technology as for operational uranium milling (Section 3.1) could be suitable, provided that the content of hazardous constituents is high enough to enable and justify this. However, to treat legacy tailings, these need to be brought in a workable condition first, e.g. by re-mining.

The reprocessing of existing tailings, which would lead to removal of hazardous constituents, in fact finalizes final remediation. Virtually no radionuclides or other toxic metals are available anymore[37] in tailings treated in this way.

Similar to operational usage, also reprocessed legacy tailings are split in up to five fractions[38]:

1) Radium (long-living radioactive waste);

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[37] By the mentioned $BaCl_2$ process together with other agents removal of radium from drainage/seepage of existing tailings impoundments is sometimes applied in the course of remediation [18]. By contrast, advanced processing does not risk actively treating long-lasting symptoms, because it already prevents from their occurrence by a preceding one-time process. Thus, it is effective much earlier.
[38] For each indicated way of disposal, see above.

2) Thorium (long-living radioactive waste);
3) Non-radioactive harmful constituents;
4) Reprocessed tailings, now virtually harmless;
5) Optionally – this would require an additional extraction step – uranium might still be extractable (depending on former processing efficiency).

However, re-opening of legacy tailings impoundments for reprocessing of those tailings needs to be decided after very serious consideration. Under the precondition of technical feasibility (e.g. increased concentration of extractable hazardous constituents), it could be justified just, if otherwise an unacceptable risk persists. Given that, a good opportunity for reprocessing might be provided, if also other criteria suggest re-opening and relocation of tailings impoundments.

4. OVERALL ADVANTAGES

Basically, the advantages deriving from advanced processing originate from:

- Extraction and removal of hazardous constituents lead to virtually harmless tailings;
- Isolation and concentration of hazardous constituents lead to an enormous volume reduction of radioactive/hazardous waste to be managed.

The concentration and isolation of hazardous constituents would transform tailings into a safely manageable form. The proposed advanced processing is advantageous: a) for states as well as b) for the uranium production industry.

a) States benefit from reducing the environmental impact leading to dramatically decreased follow-up costs:

   - As hazardous constituents become removed regular institutional control appears to be dispensable: even in the case of any loss of integrity of engineered tailings impoundments in the short term or in the long term, from a radiological point of view there is no risk of contaminant spreading (as for other removed hazardous constituents, as applicable);
   - Reduced or no need for repeated and expensive maintenance of tailings impoundments in the future.

b) The private economy (uranium production industry) can benefit from advanced processing of uranium ore in the following way:

   - No ongoing exhalation of radon;
   - Reduced or no according liability (compensation claims due to accidental tailings spreading, health risks, etc.);
   - Overall reduced operational management effort as well as less reclamation effort for due to their substantially reduced hazardousness of tailings;
   - Tailings, which result from advanced processing, do not need to be stored in such complex constructed facilities as conventionally: therefore, reduced construction effort of tailings disposal facilities is possible.
   - Less need for maintenance and monitoring of closed tailings disposal facilities due to less hazardous inventory and reduced risk;
   - While advanced processing cannot prevent from accidental spreading of tailings, but should it occur, it can substantially mitigate the environmental consequences.

Moreover, with regard to the mentioned advantages, which are achieved by advanced processing of uranium ore the uranium produced by this technology:

— Might be preferred by the state (regulators);
— Might be better accepted by the public.

The uranium deposit Kuriskova in Slovakia, which has been investigated for possible mining, could be an example for this is. Only when this mining project is approved by a local referendum would the Slovak regulator intend to issue the necessary licence [19]. Interestingly, the Canadian province Québec, following the provinces Nova Scotia and British Columbia, has decided to issue presently no permits for uranium mining, what has led to the closure of Strateco Resource's promising Matoush prospect [20]. Recently, the government of Québec stated: "how is it possible to assert that [conventional tailings disposal] technology will prove to be reliable in the longer term …?" [21]. We expect that by application of the proposed advanced processing technology it will be better possible to convince possibly concerned state and public and thus, to get licensed as well as to achieve final acceptance ('social license') of uranium production[39].

Moreover, the advantages of advanced processing might provide companies with the potential to increase in the longer term the market demand for innovatively won uranium. Thus, to apply advanced processing could once even turn into a competitive advantage.

5. ECONOMIC IMPLICATIONS

Estimates show that caring for sustainable safety already during the lifetime of operations in the end can become about five times cheaper than later remediation (e.g. [22]). Anyhow, it is evident that this would require initial investment into e.g. new components to complement existing processing lines or significant amounts of reagents.

To be confirmed by a cost–benefit analysis, we expect that possible higher initial costs are overall compensated by the above listed advantages. However, a sound cost–benefit analysis, which alone enables to determine a cost/throughput ratio, needs to take site specific conditions into account, e.g. uranium ore composition and grade as well as local disposal costs. General aspects ruling the economics, which have to be considered here, are listed in Table 1.

With regard to the mentioned advantages it appears worth to establish advanced processing as a future standard in conventional uranium mining, where indicated. Necessary for broad realization of advanced processing according regulatory requirements on the national level as well as legally binding agreements ('safeguards') on the international level, i.e. between countries producing uranium and countries having a demand for uranium, would need to come into force.

Moreover, based on correspondingly updated internationally accepted standards (e.g. IAEA Safety Standards) a certification system would need to be created for verifying implementation of advanced processing. Expert missions like those of the IAEA UPSAT tool [23] or alternative, independent audits could confirm compliance with these requirements.

[39] In very selected cases, where respective objections to the potential impact persist, even advanced processing of tailings resulting from low grade uranium ore might be considerable, though its cost–benefit ratio should be closely examined as it could, potentially, put the economic viability of a project into question. Similarly, where uranium is a by-product, a similar scenario may exist.

6. LIMITATIONS

For broad realization of the proposed advanced processing of uranium ore, where indicated it is essential to become adopted by:

- Respective regulatory requirements; as well as
- Creation of a relevant certification system.

7. DISCUSSION AND CONCLUSIONS

Even though they were thought to offer lasting solutions, the disposal of conventional uranium tailings in above ground tailings impoundments appears to not always be a final, walk-away solution. Such ways of disposal might prove, with time, to just delay environmental impacts rather than avoid them. If high grade uranium ore is processed, the same necessary level of safety, which can be ensured by the proposed removal of radium and thorium, could only be achieved by integrity of conventional tailing impoundments of more than ~20,000 years.

Currently approximately half of the world uranium production today derives from conventional uranium mining and processing. Although comprising other challenges uranium production by in situ leaching (ISL) appears to be more environmentally safe, because ISL mining avoids large surficial accumulation of tailings. On the other hand, ISL mining is limited to certain specific conditions. Therefore, it can be expected that conventional mining of uranium will continue to be of significance.

There is perhaps a growing trend of putting tailings and the worst of waste rock back underground, but this is not viable or enforced everywhere, and is itself expensive. It does, however, give an established technique against which the cost of treating tailings to make them more benign can be compared. On the contrary, not all uranium milling sites have access to a pre-existing pit where tailings can be disposed of. The costs of creating a purpose-build underground disposal pit or creating additional voids at an underground mine would be considerable.

Though also factors like regulatory/public acceptance and the related market demand for innovatively produced uranium may eminently influence an economic assessment of advanced processing, it is not possible to take these easily into account financially.

Consequently, only by the development, testing and implementation of innovative technologies like advanced processing, where indicated, may it be possible to decrease the environmental footprint of uranium mining and to achieve safety also in the long term for sites with above ground disposal.

The financial implications of advanced processing of uranium ore can comprise both cost-increasing and cost-decreasing points, which need to be balanced. However, it can be expected that more up-front investment, rather than long term repeated maintenance, is likely to be preferable over the lifecycle for states as well as for operators.

TABLE 1. GENERAL ASPECTS, WHICH NEED TO BE CONSIDERED IN A SITE–SPECIFIC COST–BENEFIT ANALYSIS

Conventional processing		Advanced processing
Processing	Present costs: - Conventional processing line; - Present operational costs.	Higher costs: - Integrated advanced processing module; - (US \$2–4M[40]) in addition to conventional processing line; - Higher operational costs.
Disposal[41]	Present costs	Lower costs (for disposal of virtually harmless tailings): - Reduced construction effort for tailings disposal facilities; - Reduced management effort, etc. Additional costs for conditioning and disposal of extracted hazardous constituents (e.g. US \$~25–50,000/m³ waste[42]).
Maintenance	Present costs	Lower costs due to in–complex tailings disposal facility.
Monitoring	Present costs	Lower costs: Tailings are virtually harmless, thus - Require less effort for the operator; - No frequent institutional control.
Reclamation	Present costs	Lower costs: Tailings are virtually harmless, thus require less reclamation effort.
Future remediation	High costs likely (if integrity gets lost with time)	None, or physical hazards only.
Liability	Very high costs possible (in case of accidental dam failure, long term health risks, etc.)	None, or physical hazards only.

[40] Note that the costs for a customized advanced processing module depend from site specific conditions.

[41] If reuse of the extracted hazardous constituents would be possible (e.g. use of radium for medical purposes, use of thorium as nuclear fuel, etc.), the total costs for advanced processing of tailings could become significantly lower as disposal costs could be minimized and extracted constituents might be sold.

[42] Rough estimation, depends from site specific conditions; by advanced processing of 1 Mt of tailings resulting from processing ore of 2 (20) % U over 6 (60) kg Ra and over 300 (3000) kg Th can be extracted and will have to be disposed of separately; disposal costs for extracted non-radioactive constituents are assumed to be lower (although their volume might be higher).

8. OUTLOOK ONTO SPECIFIC DEVELOPMENT

To develop site specific technology for the proposed advanced processing of uranium ore the following steps should be taken:

1) Advanced conceptual study including cost–benefit analysis;
2) Laboratory experiments to determine process details, followed by;
3) Transfer of the laboratory scale into pilot scale;
4) Adoption of the proposed approach by relevant regulations/implementation of respective certification.

While in the first step (advanced conceptual study) light has to be put on the full range of variety, in the second and third step the laboratory and pilot scale experiments have to address in each case the specifics of the examined tailings.

ACKNOWLEDGEMENTS

For many fruitful discussions we are grateful to B. Berg, P. Booth, P. Crochon, W. E. Falck, H.–J. Friedrich, V. Hansen, S. Hurst, A. Jakubick, C. Kunze, F. Langer, P. Schmidt, M. Sokcic–Kostic, C. Wolkersdorfer and P. Woods. The findings and recommendations are those of the authors.

This paper builds on an earlier, more general study [24].

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THE EVOLUTION OF STAKEHOLDER COMMUNICATION IN NORTHERN AUSTRALIA[43]

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Abstract

Uranium mining has been carried out in the Northern Territory more or less continuously since 1945. At the outset, involvement of and consultation with, stakeholders in general and traditional Aboriginal owners in particular was not always a major consideration and in many cases minimal at best. As the social and political scene has matured so the realization has come to all parties that inclusive stakeholder consultation, and with it the granting of the 'social licence', has become an integral part of successful and sustainable development. Indeed, without the 'social licence' new projects are unlikely to be granted regulatory approval to proceed. This paper records some of the experiences and stages of development in the stakeholder consultation processes as related to uranium mining activities in the Northern Territory since the early days, and more especially over the past 30 years. The case studies include exploration and mining activities as well as significant remediation programmes. Finally, the paper discusses lessons learned and future plans.

1. INTRODUCTION

Mining has long been an industry that has had a poor reputation with the community at large and especially in areas where poor environmental performance coupled with poor communication has resulted in the alienation of communities. This in turn has frequently resulted in poor relationships between miners and the local population and often strong feelings of resentment against mining developments. So often when mining is mentioned as possible development in a community the first reaction is one of mistrust; if the mineral of interest should happen to be uranium then a whole extra layer of concern and fear is brought into the equation. Most of the fear and concern is built around a lack of information and knowledge, although there may also have been misinformation provided to communities as well. The only way to improve this situation is for regulators and operators of mining projects to put considerable effort into developing trust with the affected communities and that requires top quality communication and the acknowledgement that serious resources have to be allocated to that activity for the whole of the life of the project.

Uranium mining always seems to arouse strong emotional responses, both positive and negative, in the debates between the various stakeholders involved in projects. Uranium is an issue where opposition is well organized on a global scale and can be relied upon to kick-in at a very early stage. But over the past twenty or thirty years, all parties have begun to realize that communication and with it the building of trusting relationships are now an integral part of the development process for any uranium mining project. One may still be prone to the whims of politicians and social commentators making statements that are designed to assuage the population rather than help decision making for new project, but this must not deter regulators and operators from ensuring that they have robust, transparent and honest communications processes in place as an integral part of the work plan from the very beginning. For this reason, the importance of communication and the consistency of the message must be promulgated throughout the workforce so that every member realizes they have a vital role to play in the

[43] Paper first presented at the Technical Meeting on Public and Community Acceptability of Uranium Mining and Milling, Vienna, Austria, December 2015.

communications strategy that will help win the trust and confidence of the community and hence the 'social licence' that will assist the project to go forward.

2. EARLY COMMUNICATIONS ARRANGEMENTS

In the early days after World War Two it appears there was very little consultation or communication with land managers or traditional Aboriginal owners when mining companies undertook exploration operations. The sole areas for discussion between Aboriginal people and miners appear to have been limited to possible employment opportunities and some background to local art and heritage sites. Although some miners did take care to log, describe and protect aboriginal art and ceremony sites, it seems that may have been all that was discussed and the objective was to benefit the miners and their experts rather than the Aboriginal people [1, 2].

However, all this began to change after 1976 following the introduction of legislation such as the *Aboriginal Land Rights Act* (ALRA). The new legislation created the Land Councils in the Northern Territory, organizations funded by, but independent of, the Australian Government. The function of the land councils was to act as advisors and supporters of traditional aboriginal people in matters relating to the land. In particular, the land councils were to act as intermediaries in consultations between mining companies and aboriginal people over access to land and the negotiation of agreements about no-go areas, jobs and future mining activities. These agreements would have the backing of the law but once a group had agreed to permit exploration they would be unable to veto mining.

In many cases the land council representative would act as an intermediary and provide the organizational and logistical support to arrange meetings between interested parties using funds provided by the mining companies. The format of many early meetings would be for the proponent to present to a group of aboriginal people then withdraw while the land council representative would explain what had been said and facilitate the discussion among the local people. Once a position had been established the proponent would be recalled and after possible further exchanges in a similar manner a final decision would be made. The problem here arose from both sides not always being confident that their point of view had been correctly translated and/or transmitted to the other party. Gradually both sides realized that a more open approach was required and that both sides should be meeting and debating without having to go through a third party, although the law required the land council to be present at such meetings to ensure the appropriate statutory actions were taking place.

It took perhaps another 10 years of gradual change before the changes were accepted as the normal way to do business. Today all successful mining companies are aware that the first step after locating an area of land is to start discussions with the traditional Aboriginal owners of that land and set about building relationships and trust. The hard part in the beginning is to establish who are the people, who are truly the appropriate traditional owners, to talk with. Here the anthropologists of the land councils come into their own as the experts on determining who can speak for the area of country where activity is proposed. Today most meetings are held on country as much as possible so that all parties can be familiar with the area as well as the work proposed. Modern audiovisual techniques and computers have made it easier to illustrate what is being proposed for exploration and mining work programmes.

3. SOUTH ALLIGATOR VALLEY CASE HISTORY

Between 1955 and 1964, thirteen small uranium mines, two small processing sites and a mill operated in the South Alligator Valley. All the operations were simply abandoned at the end of mining and no remediation action was undertaken [3]. Throughout the mining period there had been no consultation with traditional Aboriginal owners about what was happening on their land. In the mid-1980s a survey and inventory of the sites was undertaken after the valley was designated to become the third stage of Kakadu National Park [4]. At about the same time in 1986, tailings were removed from the millsite to a location outside the Park and processed to extract gold [3]. Once the park had been gazetted further actions were taken, although these did not constitute a remediation programme. From 1990 to 1992, the Commonwealth Government funded a program of hazard reduction works at all the minesites, including the mill, with the intention of reducing radiological and physical hazards for park visitors and traditional Aboriginal owners [4]. At this time, there was a limited contact with the traditional owners and a number of 'local' people were engaged to work on the programme; some of these people had previously worked with a mineral exploration company in the same area. However, it seems they were not consulted about the works to be undertaken.

But with the advent of the *Native Title Act* in 1992 it became apparent that traditional Aboriginal owners now had to be consulted and so new procedures had to be developed to recognize the changing situation. Thus in 1996, following the successful outcome of a native title claim, the land was handed back to the traditional Aboriginal owners, who in turn immediately leased back the area so it could be incorporated into Kakadu National Park as Stage 3. A specific clause in the lease required that all mine sites be fully rehabilitated by 2015. A long programme of negotiations with traditional Aboriginal owners began in 1997 with the first consultation on country. The follow-up meetings led to an agreed programme of investigations, development of rehabilitation objectives and design studies over several years which finally culminated in a successful remediation strategy being developed [5]. One important feature of the consultation was the recognition by the government side that the Aboriginal people worked to a different system of consensus agreement rather than majority decisions and so the time taken to reach an agreement was generally longer than expected.

Over time the system of meetings was refined. At first the government wanted a committee to be established and meet every 6–8 weeks. It soon became apparent that this was not going to work. The frequency was too often as meetings were quite stressful; the matter of conventional record keeping and rules of meetings was confusing to many people; the use of a facilitator was found to be often quite confusing as each side sometimes felt there was bias. In the end it became easier to deal directly with each other and have a consultative group with a majority of aboriginal members. Meetings were scheduled to take place on country and over 2–3 days in a camp as this created the atmosphere that seemed to be less stressful for members. Soon discussions became less pressured but more open and free flowing. Soon discussions touched on hitherto unmentioned subjects such as cultural concerns: gender issues for some sites, the size of machinery to be used and concerns on how drilling and blasting might impact on resting ancient spirits. These last topics illustrated how trust was developing. Also having meetings on country limited them to the dry season, which did slow up progress but did help buildup relationships as pressures were less.

Meeting formats were developed to suit the audience. The agenda was decided on the day with traditional owners being asked to write up what they wanted to discuss before the government side did. As points were discussed and agreed the outcomes were also written up on paper which was then photographed. The 'minutes' for the meeting were simply the pictures of what had been written down and agreed at the time — very easy for all members to accept that as a 'true and accurate record'. At these meetings the group shared meals in the camp and again trust developed. Group discussions were enhanced by the use of posters and models but the true value of meeting on country was to be able to offer site visits. The ability to use helicopters and four–wheel drive vehicles to show people the specific sites close up made discussions of remediation options more easily understood. Agreements were based confidently on first hand memories of what had been seen. Also, as time went on, both sides realized that it was important to keep building on experiences.

Gradually, the group became better at identifying who might be the specific custodians of certain sites so that everyone was sure the correct people were being consulted. Finally, the plan was completed and approved and funding obtained from government. Remediation work at the first two sites was completed in 2007 and the whole programme was completed in 2009 [6]. A major objective of the remediation was to ensure that the sites blended in with the surrounding countryside and would not require any special management. Monitoring continues at the present time with no planned end to the programme [7]. During the works period, a number of traditional Aboriginal owners were employed in tasks such as sacred site identification and clearance, works supervision and monitoring and stewardship as well as others who had the opportunity to learn new skills with machinery. The long term stewardship plan for the site is still to be finalized; currently routine inspections, monitoring and maintenance are undertaken by Kakadu Park rangers and staff of the Supervising Scientist.

4. CURRENT PROJECTS – RUM JUNGLE

As the South Alligator Valley project drew to a close, so another major remediation task on Aboriginal land was identified. Mining at the former Rum Jungle uranium mine was undertaken between 1952 and 1963 using open cut methods. All mining and processing operations at Rum Jungle ceased in 1971. Located about 100 km south of Darwin the uranium mine had been operated by contractors on behalf of the Australian Government; at the end of operations the site was not fully remediated. The site was cleaned up to some extent in 1977–78 but this failed to address the growing concerns regarding the impacts acid metalliferous drainage was having on the surrounding areas, particularly the Finniss River. The Australian Government agreed to fund a programme of remediation and between 1982 and 1986 a total of AUD 18.6 million was spent in treating water, collecting and containing tailings and consolidating waste rock into three piles with engineered covers [8, 9]. There seems to be little evidence that traditional Aboriginal owners were consulted throughout the early days of mine operation and cleanup and very little evidence of consultation for the remediation process. A land claim was lodged over a large area of country which included the Rum Jungle minesite. The claim was successful and all the land was handed back, apart from the minesite which was not in a state acceptable to the traditional Aboriginal owners or the regulating authorities given various safety requirements in legislation.

The conditions at the minesite were initially satisfactory but within a few years it became obvious that the remediation would not be sustainable over a long time [10]. In late 2003, the decision was made to re-examine the situation and commence studies with a view to drawing up a comprehensive remediation programme that would hopefully remediate the site thoroughly and finally. Also, the lessons learned from the South Alligator project about interaction with stakeholders were to be applied to this new project from the very beginning, particularly in relation to communications and information exchange. A comprehensive and inclusive communications strategy was employed from the outset with all major stakeholders involved and, in particular, all the appropriate traditional Aboriginal owner groups [11].

5. LESSONS LEARNED

The experiences of the past, particularly since the early 1980s, have provided a number of valuable lessons about how and why we should be ensuing that stakeholders are included as a priority in out communication plans for mining projects, be they exploration, new mines or remediation of legacy sites. The first lesson is that regulators and operators alike have to work to ensure that there is a 'social licence' to support any development. Establishing this from the very first stages of the works programme is vital to the long term success and acceptability of the project by the community. In the first instance, it is essential that every effort is made to ensure that the correct group of stakeholders is identified and engaged. This need not mean the total exclusion of others but the true traditional landowners for example need to be identified from the start so they are involved appropriately from the beginning.

Once the stakeholders have been identified it is vital to make contact with the elders or leaders and start discussions about how they wish to set up meetings with the wider community becoming involved. At all times it is necessary to remember to work at the pace set by the stakeholders and not to rush them into anything Similarly the location, style and timing of meetings has to be agreed so that the needs and expectations of all parties are addressed; this also includes the frequency of meetings – too many meetings too often will lead to a feeling of 'burn out' in the stakeholders and they will not be participating at their best, and may even decide to opt out of the process. The use of an independent facilitator is an option that should always be considered, but it may be that in some circumstances stakeholders may feel this is not an appropriate way to run meetings. Above all, it is essential to make sure that any legal requirements required in terms of notifications, processes and documentation have been complied with.

A significant issue that remains to be solved is the stewardship or long term care of remediated uranium mine sites. There is a real concern that systems currently in place may rely too much on institutional control in order to remain effective over the long term. A lot of people consider that former uranium mine sites should 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. It may also be that long term or even perpetual management of some situations (e.g. water treatment at severely impacted AMD sites) has to be considered. 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 national governments are likely to have the capability to provide adequate resources to manage the situation effectively and to the degree expected by the community. Also, economic development opportunities for stakeholders who 'inherit' the remediated sites must be optimized. The degree of 'buy-in' for local people should be maximized wherever possible. Working to monitor and maintain remediated sites is one obvious opportunity but many other small business options should be looked at to see if they can be made realistically profitable so as to maintain interest and long term involvement in maintaining the remediated sites in a safe condition.

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 remediated site and that they really do have opportunities to contribute to decision making, especially throughout the stewardship period. The ultimate goal of stewardship must be to ensure that environmental protection is paramount and maintained at the required level for the time required, again in perpetuity if necessary.

6. CONCLUSIONS

The Northern Territory mining industry in general and the uranium mining industry in particular has come a long way in the past 20–30 years in realizing that stakeholder acceptance of mining is an essential element in obtaining a 'social licence to operate'. The recognition in law of the land rights of indigenous people has been at the forefront of these changes, but other stakeholder groups have also now been acknowledged as being vital to the success in obtaining and maintain community support for mining operations. In the case of uranium mining the move to improve community acceptance has been the most noticeable, as that industry perhaps faces the most vociferous critics. Openness and transparency among regulatory authorities is also being improved as an integral part of the development process. While the main players from industry and government have made significant changes to the way they interact and communicate with stakeholders, there is still a long way to go and resources need to be made available to ensure that the improvements can be maintained and hopefully enhanced.

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URANIUM — THE SASKATCHEWAN EXPERIENCE[44]

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Abstract

In 2014, Saskatchewan was the world's second largest uranium producer behind Kazakhstan. Saskatchewan's history of uranium dates back to the 1930s with the discovery of pitchblende. Uranium production has gone through three eras; the Cold War era of the 1950s, the world energy era of the 1970s and the Federal/Provincial Panel era of the 1990s. Throughout Saskatchewan's production history, uranium and nuclear issues have remained a contentious and controversial subject. There have been multiple political parties governing the province and support for the industry has been continuous by those parties. Uranium companies have taken a very active role in educating the public and increasing support for uranium mining and become leaders in socioeconomic benefit programs and environmental protection. The uranium industry has a high level of public acceptance as a result of government and corporate responses to issues and concerns.

1. INTRODUCTION

Saskatchewan has a long history of uranium production dating back to its discovery in 1930s. The province of Saskatchewan is currently the sole producing jurisdiction in Canada and was the number one producer of uranium in the world for many years until it was overtaken in 2009 by Kazakhstan. Saskatchewan currently ranks second in world production and fourth in known uranium resources behind Australia, Kazakhstan and Russian Federation.

Uranium development in Saskatchewan, as in many locations, has been controversial and politically contentious. Its beginnings follow World War II, and the classification of uranium as a strategic mineral, through the energy crisis of the 1970s to the present day with nuclear power being recognized as non-greenhouse gas emission power generation. Current Saskatchewan operations are located in relatively remote areas with limited local populations, and are large, high grade, low cost deposits with strong economic margins.

Initially there was substantial opposition to uranium development from the public, northern residents, communities and Aboriginal groups. However, through a lengthy process of consultation, discussion and negotiation, a history of safe operation coupled with improved methods of regulation and proactive companies, the public perception of the industry has shifted from opposition to guarded and even strong support.

Saskatchewan's uranium mining industry currently maintains one of the highest rates of public support and was 86% in 2015. The Government of Saskatchewan and the uranium mining companies have maintained a high level of public acceptance for the operations through continued evolution of development policies and a supportive and proactive industry.

Saskatchewan has received national and international attention for its policies and programs for the involvement of, and socio-economic benefits for, regional Aboriginal and northern populations. The importance of social license and the commitment through all corporate levels

[44] Paper first presented at the Technical Meeting on Public and Community Acceptability of Uranium Mining and Milling, Vienna, Austria, December 2015.

of government and industry to develop and maintain a strong positive image with the public cannot be understated.

2. BACKGROUND

Saskatchewan has gone through three distinct eras of uranium production. The initial discovery and development of uranium deposits date back to the 1930s in the Beaverlodge District on the north shore of Lake Athabasca. When uranium's significance to the war effort became apparent in 1944, private staking was banned and the federal government deemed it a strategic mineral, and established the Crown corporation of Eldorado Mining Ltd. When the ban lifted in 1948, there was extensive prospecting in the area resulting in the development of 16 ore bodies and 3 separate milling facilities during the 1950s in support of the Cold War efforts. Production at the Beaverlodge operation continued until 1982.

In the second era, uranium production from the deposits of the Athabasca Basin began in 1975 at Rabbit Lake, to be followed by Cluff Lake and Key Lake. The staking rush and mine developments were in response to oil shortages and the world energy crisis. The provincial government established the Saskatchewan Mining and Development Corporation that partnered with private industry. This was also the era that introduced increased public concern and the formal public inquiry. Inquiries extended the scope of mine impact assessments to include biological effects; environmental considerations; worker health and safety; federal and provincial regulation; social, economic, community and northern benefits; disposal of nuclear wastes; proliferation and terrorism; and moral and ethical issues. The first public inquiry in Saskatchewan was the Cluff Lake Board of Inquiry (Bayda) in 1978 and involved extensive consultation throughout the north.

The current era of production is best represented by the 1990s large, high grade, low cost, deposits such as McArthur River and Cigar Lake and lower grade but significant deposits of McClean Lake and Midwest. The grades of some of these deposits were up to 100 times that of lesser deposits and the margins provided opportunities and willingness for economic benefits. Saskatchewan emerged as the sole producing jurisdiction in Canada and the provincial and federal governments merged their corporations and created the privatized Cameco Corporation. Uranium production continued to be a controversial issue and nuclear accidents at Three Mile Island and Chernobyl raised public concerns. The projects of this era went through a federal–provincial panel review process from 1991–97 that involved extensive public and northern consultation. The scope of the panel process examined the cumulative effects of the developments, social and economic benefits, plus increased environmental protection and monitoring by communities.

3. CURRENT OPERATIONS

Currently, there is one mine in decommission monitoring, three producing mines, three operating mills, one mine in care and maintenance. Corporate ownership is as follows:

— Cameco Corporation, (formed in 1988 by the merger and privatization of the federal government's Eldorado Nuclear Ltd[45] and the provincial government's Saskatchewan Mineral Development Corporation) the largest producer in Saskatchewan and the world, is the operator of three producing mines (Rabbit Lake, McArthur River and Cigar Lake)

[45] BOTHWELL, R., Eldorado: Canada's national uranium company, University of Toronto Press (1984).

and two operating mills (Rabbit Lake which processes Rabbit Lake ore, Key Lake which processes McArthur River ore);
- AREVA Resources Canada Inc., a wholly owned subsidiary of the French company AREVA, is the second largest producer in Saskatchewan. AREVA is the operator of the mine in decommission monitoring (Cluff Lake) and a mine/mill complex (McClean Lake which includes a mine in care and maintenance and a mill which processes Cigar Lake ore);
- Partners in those projects include: Denison Mines Inc. (McClean Lake, Midwest), Overseas Uranium Resource Development (McClean Lake, Midwest), Idemitsu Uranium Exploration Canada Ltd. (Cigar Lake) and TEPCO Resources Inc. (Cigar Lake);
- Several projects are in advanced stages. These include the Midwest project (AREVA) which awaits a production decision, the Millennium project (Cameco) in the environmental approval stage is on hold pending better economic conditions, and advanced exploration projects with multiple ownership including Shea Creek, Roughrider and Dawn Lake. New exploration discoveries include the Paterson Lake South deposit.

4. CURRENT REGULATORY FRAMEWORK

Under the Constitution of Canada, minerals are one of the responsibilities assigned to individual provinces, with an exception for uranium. Under provisions in the Constitution, nuclear facilities are "for the greater good of Canada" and allow the federal government to assume full regulatory authority for the operation of any nuclear facility anywhere in Canada. Under the *Nuclear Safety and Control Act*[46], uranium mines are defined as a nuclear facility. The federal agency responsible for regulating the nuclear industry is the Canadian Nuclear Safety Commission (CNSC)[47].

The other federal agencies that are involved in regulating the uranium industry include:

- Fisheries and Oceans Canada — associated with any mine impacts on fish habitat;
- The Coast Guard — associated with any impacts on water courses that can be navigated by boat;
- The Ministries of Foreign Affairs and International Trade — associated with approving exports of uranium;
- Natural Resources Canada — associated with uranium policies and statistics and ownership requirements for uranium mines;
- The Canadian Environmental Assessment Agency (in cooperation with the CNSC) in overseeing and approving environmental impact assessments associated with modifications to projects or new mine developments;
- The Canadian Customs and Revenue Agency — associated with federal income tax to which all businesses are subject.

[46] http://laws-lois.justice.gc.ca/eng/acts/N-28.3/
[47] http://nuclearsafety.gc.ca/eng/

The Government of Saskatchewan also recognizes the importance of the regulation of uranium mines and mills. The provincial regulatory role falls in three main areas:

- Environmental protection:
  - Regulates all mining related activities from exploration through development to long term monitoring and maintenance following completion of reclamation and decommissioning;
  - Principal government agencies: Ministries of Environment and Economy.
- Worker health and safety:
  - Regulation of conventional occupational and radiological health and safety;
  - Principal government agency; Ministry of Labour Relations and Workplace Safety.
- Socioeconomic benefits:
  - Regulatory and policy implementation for Employment, Government Revenues, Economic Development, Education, Training and Infrastructures;
  - Principal government agencies: Ministries of Government Relations, Economy, Finance, Labour Relations and Workplace Safety, Highways and the provincial Crown Corporation, SaskPower, associated with the supply of electricity.

Virtually all minerals in the northern part of the province, including the Athabasca Basin where uranium deposits are being mined, are owned and administered by the province. Similar to mineral ownership in northern Saskatchewan, surface lands are virtually all Crown lands — meaning that the Government of Saskatchewan owns the surface and controls the right of access to the land. Land access is not granted by virtue of mineral rights ownership. Therefore, for any mineral exploration and development activities associated with uranium in northern Saskatchewan, exploration companies and mining companies work with the province in order to secure the right to potential mineral deposits and to be able to access the land to conduct exploration and development activities.

In 2007, Saskatchewan implemented an institutional control framework for the long term management of decommissioned mine and mill sites on provincial Crown land. The Institutional Control Program governs the process for the long term monitoring and maintenance of sites when mining/milling activities have ended; reclamation and decommissioning has been completed and approved; and the transfer of the site to provincial responsibility[48].

The Government of Saskatchewan works cooperatively with the federal government on all uranium mining issues. This includes working to reduce areas of regulatory burden to ensure that the regulation of uranium mining remains efficient.

5. KEY ISSUES SHAPING PUBLIC PERCEPTION

Issues raised against uranium mining in Saskatchewan can generally be categorized into two groups. One group is the general public and a small but organized environmental lobby, and the second group is the mine proximate regional population of northerners and aboriginals.

5.1. Negative issues

The primary issues targeted by the public and environmental lobby are:

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[48] http://www.economy.gov.sk.ca/Institutional_Control-Decommissioned_Mines/Mills

— Reactor accidents (Chernobyl, Three Mile Island, Fukushima);
— Radiation concerns (gamma, radon);
— Weapons proliferation (atomic bombs, depleted uranium in Gulf War weapons);
— Nuclear waste disposal (there is no approved depository, method or plan or acceptance that it can be done safely);
— Environmental impacts.

The primary issues targeted by regional populations are:

— Socioeconomic benefits (jobs, business, revenue sharing);
— Traditional land use;
— Environmental impacts;
— Abandoned mine sites.

5.2. Positive issues

Issues raised in support of uranium mining are provided by both government and industry and include:

— Uranium mines are top ranked for safety and cleanliness;
— Multiple programs for training/hiring and high percentages of aboriginal/northern employees;
— Environmental Quality Committee (NSEQC) as communication bridge between northerners, industry, and government,
— Extensive environmental assessment and consultation processes;
— Canada ensures and is strong proponent of non–proliferation (member Nuclear Non–Proliferation Treaty, Nuclear Supplies Group, and International Atomic Energy Agency);
— Nuclear has increased recognition as clean power with no greenhouse gas emissions to meet climate change concerns;
— Nuclear generation is top ranked for safety;
— The Nuclear Waste Management Organization has public acceptance and implementation strategy for waste management;
— Saskatchewan and Canada have partnered to cleanup the abandoned sites (Gunnar and others[49]).

6. RESPONSES BY GOVERNMENT

6.1. Recent responses and positions

The Government of Saskatchewan has taken an active role in educating the public on uranium mining and responding to public concerns. The Ministry of Economy (ECON) receives frequent public input both in support of and against uranium mining. Concerns range widely from nuclear weapons to lack of employment opportunities. In all responses ECON emphasizes the uranium industry's outstanding safety records, commitment to the environment, commitments to northern employment and business, importance as a taxpayer, Canada's commitments to non–weapons proliferation and nuclear energy as a clean and viable solution to reducing greenhouse gas emissions.

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[49] http://www.src.sk.ca/about/featured-projects/pages/project-cleans.aspx

The Government of Saskatchewan's position on uranium development has its basis in the response to the Joint Federal–Provincial Panel on Uranium Mining Developments in northern Saskatchewan from 1991–97. The Joint Panel reviewed the environmental, health, safety and socioeconomic impacts of proposals for Cigar Lake, McArthur River, Eagle Point, South Mahon Lake (Midwest), McClean Lake, and Rabbit Lake/Eagle Point Expansions. Consultations were held throughout northern communities and the final report was issued in 1998. The recommendations from the Joint Panel led the government to make major changes in its regulatory framework for uranium mining and the panel process has been credited with providing education, and as a result, increased support for uranium mining in the province.

The position of the Government of Saskatchewan with respect to uranium mine development in the province was stated as follows[50]:

"The Government of Saskatchewan supports the responsible development of its uranium resources provided that individual projects:

- Adequately protect the environment;
- Provide for the health and safety of workers;
- Provide an appropriate distribution of socioeconomic benefits."

Occupational safety is very important to the Government of Saskatchewan. In 2003, the Government shared funding of a two-year federal–provincial health study for uranium workers. This study targeted mine workers who worked in uranium mines prior to 1975 and also conducted a feasibility study for extending the study to workers engaged in uranium mining since 1975.

Socioeconomic benefits are provided through government Surface Lease Agreements with the producing companies and have been successful in exceeding goals of northern employment and support to northern business.

One successful program established as a result of a recommendation of the Joint Panel that has improved northerner perceptions is the Northern Saskatchewan Environmental Quality Committee (NSEQC). Established in 1995, the NSEQC acts as a communication bridge between industry, government and northerners. It enables northerners to learn more about uranium mining activities and to see first hand the environmental protection measures being employed, and the socioeconomic benefits being gained. The NSEQC receives technical and organizational support from the Northern Mines Monitoring Secretariat (NMMS), a federal–provincial committee chaired by the Ministry of Government Relations. Increasingly, over the years, the NSEQC has become a more informed and regular voice.

6.2. The future of uranium in Saskatchewan public consultation

In 2008, the Government of Saskatchewan established the Uranium Development Partnership (UDP), to identify, evaluate and make recommendations on Saskatchewan–based value added opportunities to further develop our uranium industry. The UDP report, entitled "Capturing the Full Potential of the Uranium Value Chain in Saskatchewan"[51] proposed recommendations to expand Saskatchewan's position in uranium exploration, mining and milling into thriving

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[50] Regulating the Uranium Mining Industry: Executive Summary of the Final Report, May 1996, Saskatchewan Environment and Resource Management.
[51] http://www.gov.sk.ca/adx/aspx/adxGetMedia.aspx?mediaId=767&PN=Shared

broad–based uranium and nuclear power industries. In 2009, following the report the government announced The Future of Uranium in Saskatchewan Public Consultation Process.

The consultation process included stakeholder conferences, public hearings and meetings and correspondence. Overall, the participation confirmed that the future of uranium development in Saskatchewan is a highly controversial topic. People feel strongly — positively or negatively — about this topic, and about the long term implications of the role of uranium in the province.

The emergent themes of the public consultation were:

- Opposition to Nuclear Power Generation;
- Concerns about Health, Safety, and the Environment;
- Opposition to Nuclear Waste Disposal and Storage;
- Costs of Uranium Development;
- Support for Alternative Energy Sources: Renewables;
- Concerns about the UDP report;
- Opposition to Exploration and Mining;
- Need for Information

In 2009, the provincial government responded to both the UDP report recommendations and the public consultation report. The Government's Strategic Direction on Uranium Development response[52] outlined the government's strategic direction for uranium development in Saskatchewan and stated active support for uranium mining and exploration. The government's strategic direction on uranium included:

- Continuing to facilitate the uranium exploration and mining that has taken place in Saskatchewan for over 50 years;
- Encouraging investment in nuclear research, development and training opportunities, specifically in the areas of mining, neutron science, isotopes, small scale reactor design and enrichment;
- Reserving decisions on supporting Saskatchewan communities interested in hosting nuclear waste management facilities to when such proposals are advanced in a regulatory process;
- Directing SaskPower to continue including nuclear power in the range of energy options available for additional baseload generation capacity in the medium and long term after 2020.

In 2011, as part of that strategic direction the provincial government provided funding to establish the Sylvia Fedoruk Canadian Centre for Nuclear Innovation (SFCCNI) at the University of Saskatchewan. The SFCCNI enables Saskatchewan universities to place themselves among global leaders in nuclear research and training, creating conditions for the province to advance beyond the resource economy of uranium mining into the value added areas of nuclear innovation in medicine, materials research, power generation and environmental stewardship.

7. RESPONSES BY INDUSTRY

Industry has taken a very active role in educating the public on uranium mining and increasing support for the industry. Cameco Corporation and AREVA Resources Canada have been

[52] http://www.gov.sk.ca/adx/aspx/adxGetMedia.aspx?mediaId=1029&PN=Shared

industry leaders in northern recruitment and training, community development and environmental protection. They do annual tours to northern communities to provide operational updates and identify and respond to northern concerns. Cameco and AREVA also fund public polling to identify levels of support for uranium operations, company awareness and specific issues of concern.

Cameco has identified itself as a clean energy company and nuclear power generation is a solution to reducing greenhouse gas emissions and reaching targets set out in the Kyoto and Paris protocols. Cameco's mission statement has been, "to deliver the multiple benefits of nuclear energy to the world. Achieving this requires that our products be produced sustainably, while meeting our key measures of success — a safe, healthy, and rewarding workplace, a clean environment, supportive communities, and outstanding financial performance"[53].

An example of the uranium industry's commitment to northern Saskatchewan and policy developments to improve the public acceptance of uranium mining in the north can be found in numerous publications such as the Intergovernmental Working Group Aboriginal Participation in Mining Reports and presentations in industry fora.

Industry programs include:

- Recruitment and training;
- Education;
- Business development;
- Community development;
- Environmental protection activities.

Cameco and AREVA have partnered with local Aboriginal communities to sign collaboration agreements to guide future cooperation and sharing of benefits from uranium mining operations. The agreements set out specific commitments by the mining companies with respect to workforce development, business development, community engagement, environmental stewardship and community investment.

8. JOINT GOVERNMENT/INDUSTRY RESPONSES (PROGRAMS)

Saskatchewan's mining industry is an internationally recognized leader in both employment of Aboriginal workers, and in developing business industries with Aboriginal communities in support of mining activities. Mining companies continue to improve on this record, with increasing numbers of Aboriginal people employed in senior management positions at their mine sites. The average number of people employed at uranium mine sites in 2014 was 3,200. Residents of northern Saskatchewan make up approximately 52% of the workforce, with approximately 48% of Aboriginal descent. An additional 6200 jobs are also estimated to be associated with the uranium industry.

The uranium industry has encouraged and sponsored the development of joint ventures between experienced southern contractors and northerners in order to help Aboriginal and northern businesses to gain experience and access opportunities to supply goods and services. Areas of successful joint ventures include trucking, catering, security, janitorial, construction and underground mine development services. In 2014, the value of goods and services purchased

[53] https://www.cameco.com/about/our-vision

by the industry was CAN $1.12 billion. Over 76% went to businesses based in Saskatchewan and 39% went to businesses based in northern Saskatchewan.

The Government of Saskatchewan policy for the mining industry in the north is to encourage best efforts in providing socioeconomic benefits to northerners. The programs and regulatory instruments developed in cooperation with industry, Aboriginal communities and representative agencies include those highlighted below.

Human Resource Development Agreements (HRDA)

HRDAs are a requirement of Surface Lease Agreements signed by operating mining companies. The HRDA is negotiated between the company and the province and commits both parties to undertake best efforts to provide business and employment opportunities for northern residents.

Northern Labour Market Committee (NLMC)

The NLMC is made up of representatives of communities, Aboriginal organizations, operating industries, the provincial and federal governments, examines employment opportunities in the region and plans training programs to match those opportunities.

Multi–Party Training Plan (MPTP)

The MPTP is a partnership between the mining industry, Aboriginal organizations, communities, and the provincial and federal governments that is designed to provide training to employment opportunities for northern residents in the mineral industry. Training programs are developed for identified opportunities and timed to the need for those occupations in the industry. Initially established for a five-year term, it continues to be renewed.

These tools have strengthened the mutually beneficial relationship among the mining industry, government and northern communities. In effect, the Saskatchewan approach is not a mine by mine approach rather it is regional approach. Individual companies sign HRDAs that commit those companies to improving northern employment and business opportunities. The NLMC coordinates training requirements with educational institutions, companies and communities with funding provided through the MPTP.

Another initiative has been the establishment of the Saskatchewan Mineral Exploration and Government Advisory Committee (SMEGAC) who have developed Mineral Exploration Guidelines[54] to assist government and industry in the application and approval process for activities on land administered by the province. The guide provides information and regulatory guidelines to assist in the planning, initiation and completion of a mineral exploration program in a fashion that will help minimize environmental impacts and meet relevant legislative requirements. SMEGAC members include provincial, federal and industry representatives. The guide includes a section on how to foster and sustain effective working relations with First Nations and Métis communities.

9. OUTCOMES/ASSESSMENT (PUBLIC ACCEPTANCE)

Uranium development in Saskatchewan has at times been highly controversial and politically contentious. Public acceptance has always been linked to the end use concerns, from its strategic

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[54] http://www.environment.gov.sk.ca/Default.aspx?DN=338df889-c244-463f-b4cb-62a5721e47d3

importance in the Cold War era, the reactor accident at Three Mile Island in 1979, the Chernobyl disaster in 1984 to the tsunami damage at Fukushima in 2011. The incidents continue to cast doubt on the future of nuclear power generation and raised public concern towards the mining of uranium worldwide. The lack of storage plans and facilities for nuclear waste generated by nuclear power has also challenged support of uranium mining.

Saskatchewan's Ministry of Economy (ECON) receives frequent correspondence related to concerns on these issues and responds with emphasis on the industry's excellent safety and environmental record. Throughout the development history there has been opposition to uranium from the public, northern residents, communities and Aboriginal groups. However, through a lengthy process of consultation, discussion and negotiation, coupled with improved methods of regulation and proactive companies, the public perception of the industry has shifted from opposition to guarded and even strong support.

Support for uranium mining is linked to support for nuclear power generation (its sole customer) and the sectors of nuclear cycle. Low cost natural gas generation, renewables and reductions are increasingly reviewed against nuclear energy as methods to reduce greenhouse gas emissions. Post-Fukushima safety concerns now compete against environmental concerns as an increasing priority to the public and governments. The advancement of new technologies, and at times the misinformation on these renewable energies has also taken some emphasis away from uranium mining. ECON also receives significant public input suggesting a movement on wind and solar energy should be replacing the nuclear expansion plans being experienced worldwide.

Over the past several years, Saskatchewan's uranium mining industry has one of the highest rates of public support in its history. The Government of Saskatchewan and the uranium mining industry has maintained a high level of public acceptance for the operations through continued evolution of development policies and a supportive and active industry.

Cameco and AREVA have commissioned independent surveys on public support for uranium mining since 1990. The surveys have shown that support for uranium mining has been relatively strong over the past two decades. A significant increase in public support from 63% to 77% in 1990 to 1991 has been largely attributed to the Joint Federal–Provincial Panel process which helped educate the general public and northern communities on the benefits and safety of the uranium industry. As of December 2015, overall public support was 86% with northern support of 81%[55].

The Northern communities are most directly affected by the impact of uranium mining. Concerns raised are often environment and socioeconomic. Programs like the EQCs have helped educate the communities and Aboriginal groups and joint programs have helped provide employment and business opportunities.

In 2013, the Nuclear Policy Research Initiative at the University of Saskatchewan conducted a survey of Saskatchewan residents to gain a better understanding of the attitudinal context and policy issues related to nuclear sector activities including medicine, uranium mining, energy production and nuclear fuel waste management. The Saskatchewan Nuclear Attitudes Study[56]

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[55] https://www.cameconorth.com/uploads/downloads/CCO-Polling-Summary-01122015.pdf

[56] http://ssrl.usask.ca/npri/Nuclear%20Medicine,%20Uranium%20Mining,%20and%20Nuclear%20Fuel%20Waste%20Management%20Research%20Brief.pdf

was funded by the SFCCNI. The study showed three quarters of respondents support the continuation of uranium mining in the province, with two in five expressing strong support. Fewer than one in five respondents oppose future uranium mining.

The Government of Saskatchewan continues to receive national and international recognition for the policies and programs that have been developed over the history of uranium mining in the province, especially related to Aboriginal participation.

10. LESSONS LEARNED

The uranium industry operates in the current era of increased activism and media attention. Headlines and news can impact public opinion and the importance of communication and education should not be underestimated. Environmental groups remain a small vocal percentage of the population and their opinions and activism against the industry continue.

Regional populations stress the importance of mine specific issues and the impacts on local environments, impacts on their communities and traditional lands. They want to be heard and recognized and share in the benefits of resource development. Communication and consultation from land staking to reclamation and decommissioning must start early and be open, honest and continuous. Initiatives and programs must continuously evolve to meet increased expectations. Government programs must ensure the region shares in the socioeconomic benefits of regional resource development. Industry must recognize the importance of social not just legal license of development and the value of early and continuous consultations and be proactive in achieving those goals and not assuming that strict adherence to the letter of laws and regulations is sufficient to win public support.

Public Inquiries and joint federal–provincial panels have driven government regulation development and highlighted the importance of consultation. They provide important venues for recognition of public concern and education and awareness. Effective and regular communication increases public support of a competent and capable industry.

The general public stresses the importance of uranium end use issues including nuclear safety, weapons proliferation, nuclear waste, environmental and worker safety. NGOs are a small but vocal percentage of the population that target negative incidents and generate media attention. Some state their intent is to shutdown the industry rather than ensure its safe development. Their positions and attitudes have remained steadfast throughout. An increasing number of former anti-nuclear lobbyists have accepted that nuclear generation may have a role in meeting climate change concerns and public energy demands. Some NGOs continue to discount those opinions.

Governments and the uranium industry must recognize the importance of early, effective and regular communication and policy development that addresses public concerns. They must be prepared to respond consistently to positive and negative feedback both to uranium and the nuclear industries. They have to recognize that 100% support can never be achieved but that an educated public will support a competent and capable industry.

ACKNOWLEDGEMENTS

This paper has drawn on corporate information from Cameco Corporation and AREVA Resources Canada as well as material prepared by the governments of Saskatchewan and Canada.

SOCIAL LICENSING IN URANIUM MINING — BETWEEN ETHICAL DILEMMAS AND ECONOMIC RISK MANAGEMENT[57]

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Abstract

Mining, including mining, comes at the price of environmental and social impacts. While minimizing environmental impacts with a view to comply with regulatory requirements today is a standard procedure in mine business management, this is not necessarily so the case for social impacts. On the other hand, many societies today express their desire to participate in the decision finding on the development of their physical and economic environment. A sustained and sustainable mine development requires the collaboration with the host communities concerned, which means that it has to be developed in a process commonly termed social licensing. However, a 'social license' will not be granted once and for ever, but in fact is an evolving process, as the communities and their needs evolve. This paper examines the evolution of social licensing in the context of various ethical dilemmas and divergent norm and value systems of the different actors, such as host communities, mining companies and society as a whole. It also argued to make social licensing an integral element of business (risk) management for mining companies.

[57] Paper first presented at the Technical Meeting on Public and Community Acceptability of Uranium Mining and Milling, Vienna, Austria, December 2015. Published externally in Mineral Economics **29** (2016) 97−104.

PUBLIC PARTICIPATION AND ACCEPTABILITY OF URANIUM MINING AND MILLING IN INDIA — A CASE STUDY[58]

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Abstract

Uranium mining in India was started in 1967 by Uranium Corporation of India Limited (UCIL) at Jaduguda in Jharkhand. India has an ambitious plan to achieve 25% of electricity from nuclear power by 2050. Consequently domestic uranium production is expected to be enhanced towards meeting the fuel requirement. During the years 2003–2011, eleven environmental public hearings were conducted for uranium mining projects in different part of India. The public has favoured all the projects, with certain demands and concerns. The most common demands which have often been reflected in public hearings are employment, rehabilitation and resettlement, drinking water and electricity, healthcare, education and training facilities, recreational facilities and infrastructure. Due to widespread negative public perception against the nuclear industry worldwide and few nuclear accidents that have occurred in the past, uranium mining industry in India too faces social challenges. The effect of radiation and health issues are the most discussed topic even for very low grade uranium mining in India. Other issues raised occasionally are environmental impacts of mining. The good environmental practice and active social participation through corporate social responsibility has overcome the above challenges to make uranium mining projects of UCIL more acceptable to the society.

1. INTRODUCTION

India is a fast–developing country with population over 1.21 billion people which accounts for 17.5% of the world's population [1]. The country faces dual problems of population growth and poverty. Therefore, rapid economic growth and development is the inevitable requirement for progress of the country which may have certain impacts on various aspects of the environment. To the contrary, under development is equally responsible to induce the environmental stress. India has witnessed political, social, economic and scientific progress during the last 30 years. It is looking forward for various sources of energy to bridge the gap of demand and supply of electricity. In longer term, nuclear energy is expected to play a major role for energy security of India. The country has ambitious plans to achieve 25% of electricity from nuclear power by 2050 [2]. During the period of April 2015 to December 2015, nuclear energy generation accounted for 3.34 % of the total power generation in India [3]. Although the per capita energy consumption in India is low, amounting to 957 kWh/person in 2013–14, the future demand is expected to increase many fold [3]. The country has its three-stage indigenous nuclear power programme to cater the need of electricity demand.

Uranium mining in India was started in 1967 by Uranium Corporation of India Limited (UCIL), a Government of India undertaking under the Department of Atomic Energy which has the sole responsibility of mining and processing of uranium ore in the country. UCIL has mining operations in Jharkhand state at Jaduguda, Bhatin, Narwapahar, Turamdih, Banduhurang, Bagjataand Mohuldih. Ore from all above mines are processed at ore processing plants located at Jaduguda and Turamdih to produce yellowcake (U_3O_8). UCIL has recently added new mining and milling facility at Tummalapalle in Andhra Pradesh in the above list. UCIL has plans to exploit the techno–commercial viable deposits at Lambapur–Peddagattu in Telangana, the Kylleng Pyndong Sohiong Mawthabah (KPM) project in Meghalaya, the Gogi project in

[58] Paper first presented at the Technical Meeting on Public and Community Acceptability of Uranium Mining and Milling, Vienna, Austria, December 2015.

Karnataka and the Rohil project in Rajasthan. As a strategically important mineral product uranium is characterized as prescribed substance in the Atomic Energy Act, 1962.

Major areas of uranium occurrence in geological basin of the country are the Singhbhum Shear Zone (SSZ) in Jharkhand, the Cuddapah Basin in Andhra Pradesh, Mahadek Basin in Meghalya, Bhima Basin in Karnataka and the Delhi supergroup of rocks in Rajasthan. The entire resources of Jharkhand are located in seven major deposits which are under operation.

2. URANIUM MINING IN INDIA AND CHALLENGES

Uranium mining in India faces several sociotechnical and environmental challenges. By international standards current Indian uranium deposits are small and of low grade. The ore bodies of deposits are irregular and narrow. Consequently, large volumes of waste rock are generated to mine the required quantities of ore. Processing of progressively low grade reserves leads to production of large volume of solid waste and effluent (tailings). Hence the industry requires comparatively larger tailing disposal facilities for a given uranium production capacity. The availability of land near the processing plant which is geotechnically competent for such facilities is critical in country like India. Human settlement and population growth has resulted in lower availability of land; consequently, siting of tailing management facilities has become difficult. The problem has been aggravated owing to the local social scenarios. The transportation of fine tailing slurry (after recovery of coarse sand) to the tailing pond through closed conduits always requires special attention. Leak–proof rubber–lined steel pipelines under high pressure, which passes partially through public domain, require regular surveillance. Instrumentation and automation have been adopted for safe transportation and disposal of tailing slurry. With greater public awareness of health hazards and stringent environmental guidelines, management of tailings has become a crucial part of uranium mining.

With production of low grade ore arises the necessity of innovations in mineral beneficiation technology in order to eliminate, where possible, the transportation of entire ore from mine sites to distantly located ore processing plant and also to reduce the volume of processing. Uranium ore from various mines of UCIL in Jharkhand, which are spread over 60 km stretch in SSZ, are fed to two centrally located ore processing plants. Difficulties are faced for ore and tailing sand transportation by road due to traffic congestion and settlements along the route. Settlements around the facilities and public speculation of risks due to uranium mining pose socioenvironmental challenges for the industry. The desirable benchmark of zero discharges is a significant challenge for low grade uranium mining. A cut and fill mining method is practiced for underground mines of UCIL, where waste rock generated during mining activities is used to fill underground voids, which partially satisfies filling requirements. Coarse sand after classification of tailing from ore processing plant is used in addition to the waste rock in filling underground voids.

An irregular and narrow ore body requires many faces to be open at a time to achieve the desired production. Selection of equipment is vital issue for the Indian uranium deposits. Each mining face needs a set combination of equipment and hence deployment of multiple vehicles is required to enable the sequential activity, required for exploration and drilling, waste rock management, rock bolting, mucking and transportation. Mechanization generates vehicular emissions which require adequate dissipation for safe working environment. Split type ventilation system provides fresh air to each working face which dissipates diesel vehicle exhaust and radon gas maintaining concentrations within the mines far below the statutory limits.

3. LEGAL FRAMEWORK FOR PUBLIC CONSULTATION

The public and other stake holders have enough constitutional rights to raise the environment concerns through the mechanism of public consultation. The acts pertaining to environmental clearance, forest clearance and land acquisition which have legal provision of public consultation are:

— Environmental Impact Assessment Notification 2006 under Environmental (Protection) Act, 1986 [4];
— The Schedule Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 [5];
— The Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation and Resettlement Act, 2013 [6].

3.1. Environmental impact assessment

The Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India has notified the Environmental Impact Assessment Notification, 2006 under The Environmental (Protection) Act, 1986. Category A and Category B1 projects have to undertake public consultation for obtaining environmental clearance. Some of the projects exempted for public consultation include modernization of irrigation projects, expansion of roads and highways, building/construction projects and townships, all projects concerning national defence and security. Uranium mining has not been exempted for public consultation.

The Public Consultation has two components comprising of:

a) A public hearing at the site or in its close proximity;
b) Obtain responses in writing from other concerned persons having a plausible stake in the environmental aspects of the project.

Public consultation refers to the process by which the concerns of local affected persons and others who have plausible stake in the environmental impacts of the project are ascertained with a view to taking into account. The Public hearing is arranged in a systematic, time bound and transparent manner ensuring widest possible public participation at the project site or in its close proximity of the project by the concerned State Pollution Control Board (SPCB). The regulatory authority invites responses from the concerned person having a plausible stake by placing on their web site the Summary Environmental Impact Assessment Report (EIA report). The EIA report is made available to the MoEF&CC, SPCB, Municipal Corporation, local and village level authorities. The SPCB finalizes the date, time and exact venue for the conduct of public and advertise the same in the major national daily and one regional vernacular daily newspaper. A minimum notice period of 30 days is provided to the public for furnishing their responses. The process is supervised and presided over the District Magistrate or his representative not below the rank of an Additional District Magistrate. Videography is done for the entire proceedings. Attaching of the videotape is part of the public hearing proceedings to be forwarded to the regulatory authority. The attendance of all those who are present at the venue is noted and annexed with the final proceedings. Representatives of the proponent initiate the proceedings with a presentation on the project and the Summary EIA report. Every person present at the venue is granted the opportunity to seek information or clarifications on the project from the applicant. Response of the proponent against each quarry during public hearing is included in the final EIA report to be submitted to the Expert Appraisal Committee of the ministry for obtaining environmental clearance [4].

3.2. Recognition of forest rights

The Schedule Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 [5] is an important milestone in the history of tribal empowerment in India, especially relating to tenure security on forests and forest land. The Act recognizes and vests forest rights and occupation in forest land. The recognize rights of the forest dwelling Schedule Tribes and other traditional forest dwellers include the responsibilities and authority for sustainable use, conservation of biodiversity and maintenance of ecological balance and thereby strengthening the conservation regime of forests while ensuring livelihood and food security. Therefore, in the process of forestry clearance of the forest land for non–forest purpose, consent is required to ascertain the forest right of the dwellers. The 'Gram Sabha', a village level assembly which consists of all adult members of the village is empowered for giving consent under the act. The Gram Sabha constitutes a committee not exceeding fifteen persons as members, wherein at least one third members shall be the Schedule Tribes. Public participation is the statutory process for obtaining forestry clearance in India [5].

3.3. Right to fair compensation and transparency in land acquisition, rehabilitation and resettlement

The Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation and Resettlement Act, 2013 [6] ensures participative, informed and transparent process for land acquisition with least disturbance to the owners of the land and other affected families. It provides fair compensation to the affected families and makes adequate provisions for their rehabilitation and resettlement leading to an improvement in their post–acquisition social and economic status. When the appropriate Government intends to acquire land for a public purpose for private companies, the prior consent of at least 80% of those affected families is required. For public private partnership, consent of at least 70% of those affected families is mandatory. The consenting process includes consultation with Gram Sabha village level committees and conduct of public hearing for social impact. Public Hearing is conducted at the affected areas by giving an adequate publicity about the date, time and venue for the public hearing to ascertain the views of the affected families and to record their sayings and include it in the Social Impact Assessment report [6].

4. EXAMPLES OF PUBLIC ACCEPTABILITY OF URANIUM PROJECT IN INDIA

During years 2003–2011, the respective SPCBs conducted 11 successful public hearing for uranium mining projects of UCIL in different locations. Environmental impact assessment studied were conducted through the competent agency which includes one full season (except monsoon) baseline environmental data within study area covering 10 km radius. Project sites in Jharkhand have different demographic pattern compared to sites located in north–eastern and southern part of India. Population of the study area of the above projects varies from a low of 0.026 million at KPM project in Meghalya, to a high of 0.374 million at Mohuldih project, compared to 0.168 million at Banduhurang Mining project in Jharkhand. The population density is noted as 21 to 1191 persons per square kilometre for the above projects. The literacy rate at the study areas vary from minimum 38% at Gogi project in Karnataka to maximum 69% at Turamdih Mining project.

Overwhelming support of the nearby population had been observed in favour of uranium projects with certain demands and concerns. UCIL has its presence at Jaduguda since five decades; the public perception clearly is more favourable in the region as compared to new locations. The first-generation workers of UCIL do not perceive any risk associated with low grade uranium mining. Most of the mining site is located in remote locations which are having poor socioeconomic condition and low source of income. In such areas, the public has welcomed the projects with hope for additional opportunity to improve socioeconomic condition. However, due to limited resource availability, poor infrastructure and low employment opportunity in such project areas, the people have very high expectation from the industry. The commitment of the industry to fulfil such aspiration of the people is the key factor for the acceptance of the project. The most common issues which have been reflected during the public hearings may be summarized as below:

— Employment;
— Rehabilitation and compensation package;
— Basic infrastructure like supply of drinking water, electricity, road;
— Education and training facilities;
— Healthcare support;
— Recreational facilities.

Indian uranium mining industry too faces undue pressure due to large public perception against nuclear industry worldwide. Incidents like the nuclear power plant accident at Fukushima has further increased the risk perception associated even with low grade uranium mining. Some 'professional activists' perceive and incite the public and directly link such disaster with uranium mining activities. Often the issues being raised are similar in nature during public participation at different location and time. The public in the vicinity are prone to be unduly influenced by populist sentiment due to the low literacy rate and lack of scientific information which are always exploited by the pressure groups. Public perception of uranium mining is largely based on the adverse health and environmental impacts resulting from historical events and the few nuclear accidents have occurred in the past. The effect of radiation and health issues like infertility, still birth, congenital deformities, chronic lung diseases, cancer and life expectancy are the most discussed topics during the environmental public hearing for projects. Other issues raised occasionally are the effect of blasting and vibrations due to mining, the possibility of groundwater depletion, outbreak of water-borne diseases and other threats to human health like paralysis and malaria, and air and water pollution due to use of chemicals. Lack of scientific information in public domain and a fear of radiation have resulted in perceptions which sometimes affect the socioindustrial harmony. Likewise, the risk perceptions of people are often coloured by myths and imaginations. Diseases like paralysis, malaria and skin problem have also been apprehended due to uranium mining. UCIL considers that this fear of radiation is essentially human-made and mediated phenomenon by a small section of the media without properly checking the facts. Most of the apprehensions are based on a false understanding of the facts. UCIL has to address such issues in newer areas to counter such apprehension with more accurate information provided in a manner that can be understood by local people.

Towards this end UCIL has established information centre at Narwapahar mine in Jharkhand where scientific information on nuclear energy and its various applications in the field of health, food, industry, environment and other matters is available. Models of mining and milling process have been displayed. UCIL facilitates visits for local people, students and interested parties to the information centre for a better understanding of nuclear energy in general and uranium mining in particular.

4.1. Working experience and social factor for project acceptance

UCIL projects are mostly situated in the East Singhbhum district of Jharkhand where about 51% population is tribal. Tribes are comfortable in co-existence with nature, and adaptation of a new dimension of lifestyle sometimes creates ethical conflicts. In this area a group of tribes worship the sacred place called Jahera Sthan where the Sal tree (*Shorea robusta*) exits. *S. robusta* is the dominant species in this area. The presence of such trees in the project area causes conflict of interest. Handling such sensitive issues need patience and good social relationship. Such locations may be avoided if possible to maintain the long term industrial harmony. UCIL has compromised a considerable volume of tailing storage facility to protect the Jaher Sthan in tailing pond area. Availability of tailing storage facility is critical parameter for life of mine and ore processing facility in country like India where population density is high. It has also been experienced that sometimes date of festival of the tribes, which continue for several days, coincide with the date of public hearing. Such situation has led to postponement of public hearing date. Protection of sentiments of the local tribes is equally important for project acceptance.

5. A WAYS TO OVERCOME CHALLENGES

UCIL has vast experience of uranium mining for last five decades with technical excellence. The various difficulties in mining have been overcome with good management practice and active social engagement with nearby population.

5.1. Environmental Management System

The state of the art Health Physics Unit (HPU) of the Environmental Assessment Division of the Bhabha Atomic Research Centre (BARC) has sole responsibility for radiological surveillance of the operations. The HPU of Jaduguda was established in year 1967 before inception of mining activity at Jaduguda. HPU is an independent agency, which keeps vigilance on industrial operations and imparts training on radiological aspect to the employees and the public. UCIL has established a separate section “Environmental Engineering Cell” to carry out day–to–day non-radiological environmental monitoring and inspection of its operations. The environmental management system of UCIL comply the guidelines as per ISO: 14001:2004.

5.2. Corporate Social Responsibility

UCIL considers the location of its projects in remote areas as a unique opportunity to serve the local population and bring a change in their lives. Corporate Social Responsibility (CSR) has proved an excellent tool to achieve the above goal and has enabled the project acceptability to the society up to satisfactory level. The Companies Act 2013 has mandated to spend at least 2% of average profit of last three preceding years for corporate social responsibility.

The uranium mining projects in Jharkhand has facilitated peripheral socioeconomic upliftment. UCIL undertakes an active role in CSR activities for peripheral development of the nearby area in the field of health, education, drinking water, sports, social infrastructure development, animal care, women empowerment, skills development and other matters. Medical camps nearby villages are being conducted by UCIL hospital on periodical basis. Medicines are provided to the patient free of cost. Senior officers accompany with medical teams and educate the villagers about health and hygiene. Some economically deprived students from nearby area are selected for free education under Talent Nurture Programme. Financial support is provided to nearby schools. Training centres of UCIL collaborate with expert to impart job–oriented training to local tribal women to facilitate direct and indirect employment opportunity. UCIL provides market facility for local agricultural produce. An Industrial Training Center has been established to impart technical training to the land displaced and youths of nearby villages. Football (soccer) and archery are the favoured games in Jharkhand. UCIL support the locals Sports Councils of villages by providing sports material and the construction of playgrounds.

6. DISCUSSION, SUMMARY AND CONCLUSIONS

For energy security of India, the growth of nuclear power is inevitable. India has planned to achieve 25% of electricity from nuclear power by 2050. UCIL has sole responsibility for uranium mining and milling in India and intended to set up new facilities to enhance its production capacity. Public acceptability of the projects is the key factor to achieve the target for nuclear power program. The public and other stake holders have enough constitutional provision to register their voice for environmental concerns through the mechanism of public consultation. The public has favoured the UCIL projects in different part of India, although with certain demands and concerns which have been raised during public hearings. The first–generation workers of UCIL do not perceive any risks with low grade uranium mining. The most of mining sites are located in remote locations which have poor socioeconomic conditions and low sources of income. In such areas, the public has welcomed the uranium projects with hope for additional opportunity to improve their socioeconomic condition. Such a scenario in the project areas calls for very high expectation from the industry. The commitment to fulfil such aspirations of the people, where this is reasonable and possible, is the key factor for the project acceptance. The common issues which have been reflected during public hearings are employment, rehabilitation and compensation package, demand for drinking water, electricity, education and training facilities, healthcare and basic infrastructure.

Indian uranium mining faces several challenges due to a legacy of public perception against nuclear industry worldwide. Public perception largely talks about adverse health effects like infertility, still birth, congenital deformities, chronic lung diseases, cancer and low life expectancy. Environmental impacts are speculated such as effects of blasting and vibrations due to mining, the possibility of groundwater depletion, and air and water pollution. A general lack of accurate scientific information in the public domain and an apparently largely externally–motivated, exaggerated fear of radiation has resulted negative perception for nuclear industries. The disease like paralysis, malaria and skin problem has also apprehended due to uranium mining. Most of the apprehensions are based on a false understanding of the facts. UCIL has to address such issues in upcoming project areas to nullify such public concerns. Due to low grade deposits, the projects require comparatively large tailing disposal facilities. Human settlement and population growth around the facilities draw special attention for environmental management.

The various difficulties have overcome with good environmental management practice and active social engagement. CSR activities have proved an excellent opportunity to address above challenges and make uranium mining projects of UCIL more acceptable.

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ENVIRONMENTAL ATTRIBUTES OF MINING AND PROCESSING OF URANIUM ORE IN SINGHBHUM, JHARKHAND, INDIA[59]

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Abstract

Like any industry, several environmental attributes are associated with mining and processing of uranium ore. The environmental attributes mostly originate from nature of the deposit which in turn depends on series of governing factors such as grade mined, methodology of mining, processing and waste management, climatological conditions and nature of the discharge. Environmental attributes for facilities carrying out mining, processing and waste disposal in close proximity mostly include release/emanation of radon, long lived alpha activity in the particulate, gamma level variation due to waste rock and tailings slurry disposal and possible migration of dissolved radio nuclides into hydrosphere and lithosphere. In accordance with existing regulatory guidelines, proper management of waste is ensured to address the environmental concern during operational and/or post–operational phases. This paper summarizes the features of uranium mining, ore processing and waste management, key environmental attributes pertaining to radiological concerns, monitoring results of diverse matrices for operational facilities of Singhbhum, India and the regulatory approach.

1. INTRODUCTION

Mining and processing of uranium ore was started in Singbhum district of Jharkhand State of India almost five decades ago and the industry has chronologically diversified with the present status of six underground and one open cast mines with two ore processing and waste disposal facilities in this region. Uranium mining and processing in India is carried out with laid down procedures that incorporate latest technology that can address core issues raised in the context of radiological protection and environmental attributes. To minimize the environmental impact during mining, processing and disposal of radioactive waste appropriate control measures such as use of waste rock within the mines, release of gaseous radon with sufficient atmospheric dilution, treatment of liquid effluent prior to discharge and disposal of solid tailings of the process plant in well thought–out, engineered impoundment systems (tailings ponds) are exercised. Assessments made based on regular surveillance within the facility and the adjoining areas provide sufficient input for long term planning for environmental protection. This paper provides an overview of the industrial process pertaining to mining, processing and management of radioactive waste and results of monitoring of external gamma level, atmospheric radon and various environmental matrices such as air, water and soil.

2. BRIEF DESCRIPTION OF INDUSTRIAL ACTIVITIES

2.1. Uranium mining

There are six operating uranium mines (Jaduguda, Bhatin, Narwapahar, Turamdih, Bagjata and Banduhurang) in this region within a distance of approximately 60 km. Excepting the Banduhurang opencast mines, other mines are underground with varying grades of deposits [1]. Latest mining methodology is adopted in new mines and old mines are upgraded to comply with the national safety regulations. The oldest uranium mine at Jaduguda has been developed

[59] Paper first presented at the Technical Meeting on Public and Community Acceptability of Uranium Mining and Milling, Vienna, Austria, December 2015.

up to a depth of 900 m in three stages. The central shaft serves as entry of workers and material and as main ventilation intake route [2]. The mining is carried out using latest machinery and transported to ore processing unit through conveyer belt. A system of exhaust fans located in adits at the top provides adequate air to ventilate the mine workings. The ventilation system is continuously upgraded to provide air quantity commensurate with the operations [3]. Latest available technology of the country has been adopted in the development of latest mines at Bagjata, Narwapahar and Turamdih. Trackless mining with decline is used as one of the entries to excavate the ore. Ventilation in these mines is through a combination of decline and shaft with high capacity exhaust fans. The mined ore is transported to ore processing plant either through conveyer belt or using transport vehicle.

2.2. Ore processing

Uranium ore from the six mines are processed at two centralized ore processing unit at Jaduguda and Turamdih. At Jaduguda, processing is done for Jaduguda, Bhatin, Narwapahr and Bagjta mines, whereas, at Turamdih processing is done for Turamdih and Banduhurang mines. The uranium ore contains soluble hexavalent form as well as insoluble tetravalent form of uranium (oxide ore which is a combination of UO_3 and UO_2). The ferrous iron content of the ore is excess as compared to the ferric iron, however, for oxidation of tetravalent uranium excess ferric iron is required. For this conversion, pyrolusite is used as an oxidant which ensures oxidation of ferrous iron to ferric state. Leaching of the ore is carried out in sulphuric acid medium in presence of this oxidant. The leached slurry is filtered using drum filters and pre–coat filters. The filtered liquor containing uranium is passed through ion exchange resin where uranium is adsorbed. The column is eluted using brine solution and product (magnesium diuranate) is recovered by adding magnesia [4–6].

2.3. Radioactive waste management

2.3.1. *Solid waste*

2.3.1.1. Waste rock from the mines

During ore winning operation economically less viable portion of the rock is removed which contains traces of uranium (depending on the cut-off grade) and associated radionuclides. Even though, not economical for product recovery, their proper management is required for radiological protection of the environment. The waste rock from the industry is partly used as backfill material in the mines or as landfill in controlled areas (within the premises) of limited access.

2.3.1.2. Waste cake from filtration unit

During ore processing the leached slurry is subjected to filtration, the solid residue of the filtration unit is called ‘waste cake’. This solid mainly contains insoluble fraction of the ore containing radiologically significant elements of the ^{238}U decay series. The treatment of waste cake is carried out at Tailings neutralization plant along with the barren liquor from the ion exchange column.

2.3.2. *Liquid waste*

2.3.2.1. Barren liquor

Barren liquor is the major portion of liquid waste generated during processing of uranium ore and is coming out from the ion exchange column. Barren liquor with low pH contains un-extracted fraction of uranium along with dissolved radionuclides like ^{230}Th and ^{226}Ra. Barren liquor is mixed with waste cake from the filtration unit and treated at Tailings neutralization plant.

2.3.2.2. Mine effluent

The effluent from the mines is collected and pumped to the ore processing unit where it is partly reused after clarification. Excess effluent is sent to the effluent treatment plant where it is further treated and discharged after removal of radiologically significant elements. Apart from radiological toxins other toxins such as heavy metal is also removed in this process.

2.3.2.3. Mill effluent

Floor washings of the mill, overflow from neutral thickeners and other equipment form the inventory of mill effluent. Effluent from the mill is sent to effluent treatment plant for treatment prior to its disposal.

2.3.3. *Gaseous waste: exhaust gases from the mines*

Radon and its progeny constitute major source of gaseous waste from the mines. Well-designed ventilation system for dilution of radon and its progeny as well as large atmospheric dilution ensures the safe discharge of the exhaust gases into the atmosphere [3].

3. TAILINGS TREATMENT

Waste cake from the filtration unit and barren liquor from the ion exchange column are mixed together and neutralized to a pH 9–9.5 using lime. The slurry is separated into coarse and fine fractions. Coarse fraction is sent to the mines for back filling and fines are discharged into an engineered impoundment system called tailings pond [7]. At the tailings treatment plant radionuclides like ^{230}Th and chemical constituents like manganese get precipitated.

4. TAILINGS POND

The tailings pond is an engineered impoundment system for the process waste. There are natural hills on three sides an earthen bund forming the fourth side. Design features of the earthen bund are based on nature and quantity of tailings, local geological features, sustainability under abnormal situations such as heavy rain or flooding. Fine solids of the slurry settle in the pond and the overflowing liquid, through a set of decantation well is led to the effluent treatment plant in concrete channels. To minimize resuspension of dust and to consolidate the tailings, vegetative cover is provided which includes *Typha latifolia*, *Saccharum spontanium*, *Ipomoea carnia* and others.

5. EFFLUENT TREATMENT PLANT (ETP)

Excess effluent generated from mines and mill and that overflowing from the tailings pond are directed to effluent treatment plant. The effluent is collected in hold up tanks. Further it is clarified and subjected to barium chloride and lime treatment. Barium chloride treatment ensures the removal of radium below the levels prescribed by regulatory agencies. Lime treatment is for removal of dissolved uranium and manganese. Finally, flocculent is added for effective settling. The underflow is pumped to mill where it is mixed with fresh tailings and discharged at tailings pond. Overflow after maintaining the pH and ensuring regulatory compliance is discharged into the nearby surface water stream [2, 8].

6. MONITORING METHODOLOGY

External gamma radiation dose rates around the facilities are monitored using gamma survey meter with multiple detectors (Identifinder 2). Atmospheric radon (^{222}Rn) is measured using Alpha Guard instrument in diffusion mode and a low level radon detection system, which is an electro–deposition passive radon monitoring system [9]. ^{226}Ra is estimated by an emanometric technique in which the ^{222}Rn daughters are allowed to buildup for a known period. The accumulated radon is collected in a scintillation cell and counted after equilibrium (between radon and its short lived progeny) is attained [10]. Uranium (natural) is measured by UV and LED based fluorimetry [11, 12]. In the former technique, chemically separated uranium is fused with a fusion mixture (NaF–Na_2CO_3) and subjected to UV radiation in a fluorimeter in the later technique a fluorescence enhancing agent and a buffer such as sodium pyrophosphate is added and fluorescence intensity is measured. The intensity of the fluorescence is proportional to the amount of uranium present in the sample. The 3650A° excitation and 5546A° fluorescence wavelengths are unique to uranium [12]. The quality of the analyses is checked by analyzing IAEA or Bureau of Analyzed Samples (BAS), UK supplied certified reference materials.

7. RESULTS AND DISCUSSION

7.1. Radiation levels

The grade of uranium mined in India is low, and accordingly specific activities of its waste rock and tailings (process waste slime) are expected to be low. The gamma radiation levels, which are a function of grade of uranium mined and processed, originating from these low specific activity materials, are of the µGy range. The ^{226}Ra content of the tailings at both sites varied within the range of about 4–8 Bq g^{-1}. The gamma radiation dose rates at 1 m directly above the tailings pile range from about 0.75–3.3 µGy h^{-1}, averaging around 1 µGy h^{-1}. This reduces to about 0.2–0.5 µGy h^{-1} on the embankment and attains the local background levels of 0.10–0.20 µGy h^{-1} within a short distance from the embankment. The annual radiation dose rates measured by thermoluminescent dosimeters in the public domain around the uranium facilities are comparable to natural background levels in the region and vary from 901 to 1738 µGy y^{-1}, averaging around 1128 µGy y^{-1}. The maximum value was found within the mines facility at Bhatin. The dose rates at few metres away from the tailings pond waste depository were similar to the levels observed at distant location from tailings pond within the uranium mineralized area.

7.2. Radon

Atmospheric radon levels are periodically measured adjoining the mining, ore processing and tailings management facilities of Singhbhum. Distance away from the facilities is also periodically monitored for atmospheric radon. For instance, a typical annual average radon concentration around Bagjata mining region was 28 ± 11 Bq m^{-3}, around Jaduguda 35 ± 7, Narwapahar are 25 ± 9 and Turamdih around 25 ± 5 Bq m^{-3}, respectively. Difference in concentration in areas in the vicinity of the tailings depositories and away was insignificant.

Typically, radon concentration on the tailings pond was ranging between 40–75 Bq m^{-3}. Atmospheric dilution reduces the radon levels to normal background levels of the region within a short distance. Diurnal and seasonal variation of radon concentration in air was also observed. Estimates of radon level in the environment and inhalation doses from radon and progeny has previously been done which is in accordance with the present investigation [13–15].

7.3. Surface water

The effectiveness of the effluent treatment plant in controlling the release of radioactive materials to the aquatic environment is evaluated by measurement of U and ^{226}Ra in the inlet and outlet effluents. The U and ^{226}Ra concentrations observed in the incoming effluent at Jaduguda were found to vary from 11–1145 µg L^{-1} and 3.7–409 mBq L^{-1} with median concentrations of 47 µg L^{-1} and 156 mBq L^{-1} respectively. The concentration of U in treated effluent at Jaduguda ranged from 1.2 to 7.7 µg L^{-1} with a median concentration of 2.7 µg L^{-1} and ^{226}Ra concentration ranged from 3.5 to 176 mBq L^{-1} with a median concentration of 4 mBq L^{-1}. The U and ^{226}Ra concentrations observed in the surface waters of nearby river of Jaduguda were found to vary from 2.2–55 µg L^{-1} and 3.6–45 mBq L^{-1} with median concentrations of 7.8 µg L^{-1} and 10.5 mBq L^{-1} respectively. The Gara, a relatively small river and tributary of the Subarnarekha River, receives the treated effluents from the uranium mining and milling industry. The median U and ^{226}Ra concentrations in water from the Gara and Subarnarekha Rivers downstream of uranium mining operations are nearly of the same order as the respective background levels observed upstream. Typically, U and ^{226}Ra concentrations observed in the surface waters of nearby stream of Turamdih were found to vary from 2.2–16 µg L^{-1} and 4–20 mBq L^{-1} with median concentrations of 9.1 µg L^{-1} and 7 mBq L^{-1} respectively. The Dhatkidih Nala, a relatively small stream and tributary of the Kharkai River, receives the treated effluents from the uranium mining and milling industrial facilities at Turamdih. The median U and ^{226}Ra concentrations in water from the Kharkai and Subarnarekha Rivers downstream of uranium mining operations are nearly of the same order as the respective background levels observed upstream. The median concentration of U and ^{226}Ra in the immediate surface water recipient stream are well within the respective derived water concentration (DWC) limits [15]. The levels in Subarnarekha and Kharkai perennial rivers of this region are even lower and approach the regional background values.

7.4. Groundwater

To observe the migration characteristics of radionuclides from tailings pond to the adjoining hydrosphere, seven monitoring wells are constructed around the tailings pond at Jaduguda and ten monitoring wells are constructed around the tailings pond at Turamdih. The results are presented in Tables1 and 2. Comparing the results with untreated tailings effluent, it has been observed that the concentration of radionuclides in monitoring wells are much lower reflecting the capability of the multilayer barrier to inhibit the migration of contaminants into adjoining hydrosphere. Decontamination efficiency of effluent treatment plant is more than 95% for significant radionuclides U and ^{226}Ra.

TABLE 1. MEDIAN CONCENTRATION OF RADIONUCLIDE IN MONITORING WELL WATER EFFLUENT AROUND TAILINGS POND AT JADUGUDA (2013–14)

Monitoring well No.	U(nat) $\mu g\ L^{-1}$	^{226}Ra mBq L^{-1}
1	1.6	60
2	1.9	33
3	2.7	29
4	1.9	21
5	2.2	10
6	3.2	10
7	1.7	19.5
DWC* Limit	60	300

* Drinking Water Concentration — see text.

TABLE 2. MEDIAN CONCENTRATION OF RADIONUCLIDE IN MONITORING WELL WATER AROUND TAILINGS POND AT JADUGUDA (2013–14)

Monitoring well No.	U(nat) $\mu g\ L^{-1}$	^{226}Ra mBq L^{-1}
1	1.1	9
2	0.9	11
3	3.2	10
4	1.4	18
5	0.8	11
6	2.1	26
7	4.3	17
8	1.1	25
DWC Limit	60	300

Approximately five hundred tube-well and well samples were collected from adjoining areas of tailings pond and at distances away from tailings pond. Comparable concentration of radionuclides was found in samples from drinking water sources in the vicinity of tailings pond and away. Median radionuclide concentrations were much lower than the respective derived limits of 60 $\mu g\ L^{-1}$ and 300 mBq L^{-1} followed in India [15]). The concentratiosn of uranium and ^{226}Ra in groundwater around Jaduguda have previously been studied extensively [16].

8. SOIL

Soil samples are regularly collected from various locations around different facilities especially the tailings ponds area of Jaduguda and and Turamdih and analyzed for uranium and ^{226}Ra. Median concentrations of analytical results of 130 samples (covering the areas around each facility including mining sites at Narwapahar and Bagjata) are presented in Table 3. The other sites such as Banduhurang and Bhatin are in close proximity of Turamdih and Jaduguda so adjoining areas are covered along with these two sites. The results indicate that natural radioactivity levels in soil from the tailings pond area is of the same order as found elsewhere in the region. The variation is due to natural fluctuation only [17].

TABLE 3. ACTIVITY CONCENTRATION OF RADIONUCLIDES IN SOIL AROUND URANIUM MINING AND ORE PROCESSING FACILITY (2013–14)

Distance from the facility	N	U(nat) mg kg^{-1}	^{226}Ra Bq kg^{-1}
Jaduguda			
0.5	5	2.8	25
0.5–1.6	4	2.6	35
1.6–5	4	2.1	44
5–10.0	4	3.3	53
>10	3	1.9	42
Turamdih			
< 1.6	20	1.5	23
1.6 – 5	24	1.7	31
5 –10	16	1.8	36
Narwaphar			
< 0.5	4	1.1	23.4
0.5–1.6	4	1.3	35.5
1.6–5	8	1.4	39
5–10	10	1.6	41
Bagjata			
0.5	5	2	52
0.5–1.6	4	3.6	89
1.6–5	4	3.1	47
5–10	4	2.9	60
> 10	3	2.2	57
Solid tailings	Typical range	50–75	4000–7800

9. LONG LIVED ALPHA ACTIVITY IN AIR

The long lived gross alpha activity in respirable size dust varied from 1–2 mBq m^{-3} in the proximity of the facilities and at different distances away from the facilities.

10. REGULATORY FEATURES AND PUBLIC PARTICIPATION/AWARENESS

Both for operating plants and new projects licensing/clearance are obtained from various National Regulatory Authorities. These regulations are followed during the different stages of operations of the mines. After licensing/clearance there is provision of periodic review of the status of the environment [18, 19]. Public awareness program is conducted for the common people, students, school and colleges about the steps carried out to ensure the environmental safety during the mining operations [20]. Students are encouraged in environmental laboratories to undergo basic training in different aspects of radiological and environmental protection.

11. CONCLUSION

The state of art technology adopted by uranium mining and processing industry of India and regular surveillance/monitoring ensure safe environmental operations of the facilities. The innovative technology adopted in uranium mining and processing industry of India and regular radiological surveillance/monitoring ensure insignificant environmental impact in and around the facilities. The environmental monitoring around the site demonstrates that controlled discharges from these facilities for decades have not altered the pre–existing radiological status of the environment.

ACKNOWLEDGEMENTS

The authors are grateful to K. S. Pradeepkumar, Associate Director, HSE Group, Bhabha Atomic Research Centre, Mumbai, for his encouragement to carry out the work. Authorities of UCIL for extending necessary facilities during the course of this work are also acknowledged. The authors also acknowledge the help and support received from colleagues working at Environmental Survey Laboratories of Bhabha Atomic Research Centre situated in Singhbhum region.

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FROM CRADLE TO GRAVE: MANAGING THE CONSEQUENCES OF FAILING TO ENGAGE INDIGENOUS PEOPLE IN THE WHOLE OF MINING PROCESS[60]

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Abstract

This paper briefly examines how indigenous engagement by Australian mining companies has evolved over the past 50 years and highlights some of the negative consequences that can arise from ineffective cross-cultural consultation. A special focus is placed on uranium mining and milling and a specific engagement strategy for the Ranger Uranium Mine is discussed as a case study. From this, a more general strategic approach based on cultural recognition is proposed. Outcomes for the Ranger Uranium Mine have so far been promising, but further work is required to determine if the general strategic approach will be successful.

1. INTRODUCTION

The inherently destructive nature of mining means that failure to obtain community support can create significant financial and emotional backlash against individual mining companies and ultimately, the wider industry. Acquiring community support is made harder where communities are affected by past negative legacies of mining or where people hold different worldviews to those of company management. This can be a particular problem for mining companies working close to remote Aboriginal communities, who continue to live in a culture where people do not generally differentiate between the spiritual and the natural environments. Such communities often perceive damage to the environment as an attack on their way of life.

The 'social license to operate' is a concept that directly reflects the degree of support a company has obtained from affected communities for its proposed actions. Much social friction is caused by cultural differences, past actions of mining companies and in the case of uranium mining the actions of third parties using the mines' products. Unless these issues can be adequately resolved, communities are unlikely to support new mining projects. Where support is not forthcoming, the 'social license to operate' will not be attained and negative consequences to the company (e.g. high legal costs or loss of the resource) and the community (e.g. loss of opportunities) is likely to follow. To engender support and obtain their 'social license', companies are now obliged to undertake a high level of community engagement, much of which is of a cross–cultural nature.

Australia's Northern Territory represents an ideal area for study of Aboriginal community engagement practices because of its large indigenous population and the close proximity of many uranium deposits to remote communities where Aboriginal culture remains strong. There is also a relatively long history of interaction between Aboriginal people and mining companies which provides detailed background information related to how engagement has changed over time. By examining the nature of those changes, past mistakes may be corrected and solutions applied to improve existing engagement strategies.

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[60] Paper first presented at the Technical Meeting on Public and Community Acceptability of Uranium Mining and Milling, Vienna, Austria, December 2015.

2. A SHORT OVERVIEW OF ABORIGINAL ENGAGEMENT IN AUSTRALIA'S NORTHERN TERRITORY

The principle historic events that have brought change to indigenous engagement practices over the history of uranium mining in Australia's Northern Territory are summarized in Figure 1. Set against the timelines for development, operations and closure of a number of mining projects, it becomes evident that accessing a uranium resource has become more difficult as community awareness has increased and business practices move towards sustainable outcomes.

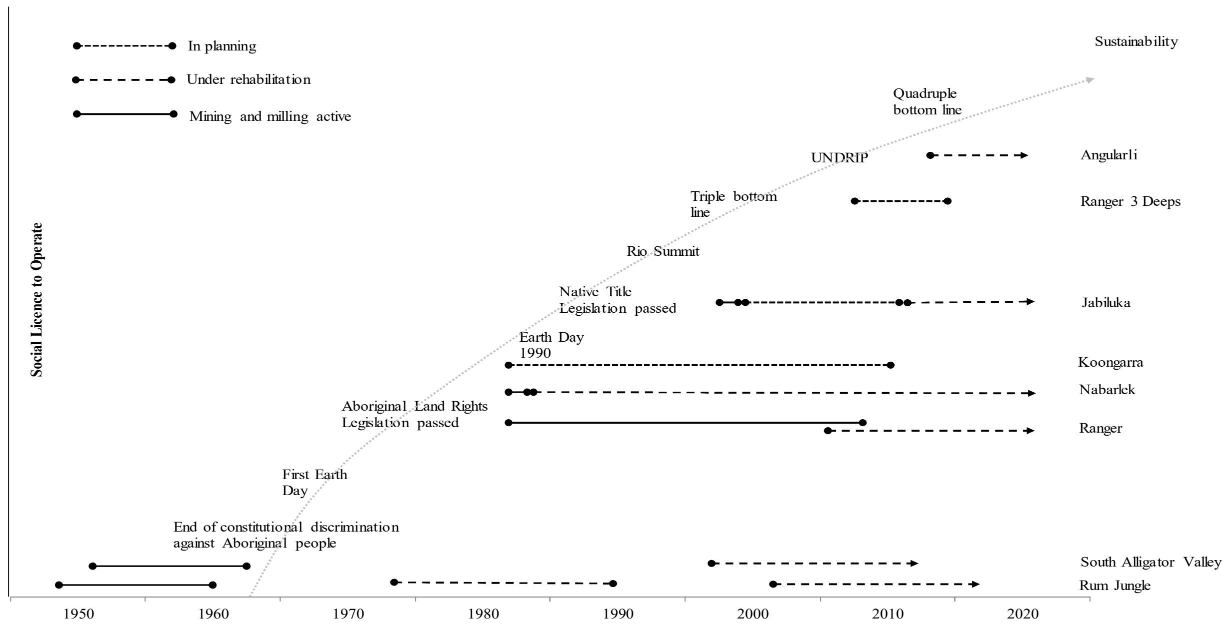


FIG. 1. Major external events and their impact on uranium mining in Australia's Northern Territory.

Figure 1 demonstrates that it has been less than 50 years since Aboriginal people have been recognized as important stakeholders and, as a consequence, outcomes of previous poor engagement practices remain etched in the memory of many Aboriginal people and continue to be passed on through the stories told to their children. In the period prior to the late 1960s, engagement was virtually non-existent and Aboriginal people were generally excluded from all aspects of mining practice. Little thought was given to rehabilitation of mines and once mining was complete, companies walked away with few thoughts to the consequences that surrounding Aboriginal communities would face.

1968 represented a watershed of political change in Australia that ultimately had profound effects on how engagement with Aboriginal people would develop. The general populace was becoming more aware and discrimination against Aboriginal people was effectively ended following a referendum after which the Commonwealth Government assumed control over Aboriginal affairs. This change eventually led to a period where the rights of indigenous people slowly developed in conjunction with a broader concern for the natural environment, not only in a national, but a worldwide context. Legal recognition of Aboriginal rights followed in the 1970s, along with tighter environmental legislation. Restrictions that stemmed from a government decision to limit uranium mining to three mines only were in place. Consequently, the mining industry was being pushed into a position where it needed the support of Aboriginal people if its projects were to proceed.

The 1980s and 1990s was a period where the risks of nuclear power generation were brought to the world's attention through incidents at Three Mile Island and Chernobyl. In addition, advancing indigenous rights and public concern about uranium mining in close proximity to Kakadu National Park had spilled over in the form of anti-uranium protests by the mid-1990s. There were open displays of dissatisfaction caused by perceptions that Aboriginal rights, Aboriginal culture and international conventions were being disregarded or ignored; and that the mining industry continued to use a heavy–handed legal approach to resolve its inability to access Aboriginal lands.

Significant change did not occur until the early 2000s, when a drive towards sustainable long term outcomes according to principles such as the quadruple bottom line, had begun to dominate the political and business landscapes. The value of the 'social license to operate' was recognized and mining companies focused more on their corporate social responsibilities, including how to deal not only with their own financial viability, but also with outcomes related to environmental, social and cultural impacts.

Despite the ongoing improvements to the standard of engagement with Aboriginal communities, many historic issues continued to impact on the progress of uranium mining. Some of the longer term consequences included the loss of the Koongarra deposit to mining in 2013 [1], suspension of mining at Jabiluka in 2004 [2–3] and an uncertain future for new projects, such as Ranger 3 Deeps [4–5]. To industry, this represents a collective estimated loss of about 126 000 tonnes of uranium at a current (2016) market value of US$9.7 billion [6]. Closure of projects such as Rum Jungle and South Alligator Valley are now being addressed in a period characterized by increased dissatisfaction with mining legacies; more complex requirements; increased cost; a general distrust of the mining industry and concerns about how human health has been and will continue to be impacted.

Legislation and philosophies of engagement have progressed significantly over the past 50 years, yet many companies still struggle to come to terms with dealing with Aboriginal communities. This has resulted largely from an increased resolve among Aboriginal people to protect their way of life within a dominant society with which it has few fundamental cultural commonalities. For their part, many companies have yet to develop effective cross-cultural management systems that are in-depth and suitable for the unique cultural environment in which they must work. To reach this position, new approaches and culturally appropriate tools should be designed and applied if further negative consequences are to be avoided. This paper discusses work that has been undertaken with Aboriginal people affected by the Ranger Uranium Mine and provides a strategy that may serve as useful guidance for companies seeking to improve their own cross-cultural systems.

3. CASE STUDY — RANGER URANIUM MINE

Ranger Uranium mine, located in the Alligator Rivers region in Australia's Northern Territory is one of the world's best known and most scrutinized uranium mines. It is located on freehold Aboriginal land, within a tropical environment contiguous with the World Heritage listed Kakadu National Park and Ramsar listed Magela wetlands. Mirarr–Gundjeih'mi, the traditional Aboriginal owners of this land, have assisted in developing a robust strategy that is designed to meet their cultural requirements while also being applicable to operations at all phases of mining.

The starting point of this process was to consider the wider politics involved during development of the Ranger mine. In the mid-1970s, several important political actions were in process. Aboriginal Land Rights Legislation was being implemented, the boundaries of Kakadu National Park were being negotiated and the Ranger, Koongarra and Jabiluka deposits had been found. Following an inquiry into uranium mining in the region [7–8], the Government adopted a position that "their [Mirarr] opposition [to uranium mining] shall not be allowed to prevail" [8], setting the stage for 30 years of difficult Aboriginal stakeholder engagement and the development of the burdensome legal and regulatory approach shown in Fig. 2.

Subsequent events at the nearby Jabiluka and Koongarra mines became entangled because of their proximity to Ranger and because of close family links between Aboriginal landowners. These events included claims that an agreement was signed under duress, the sacred Boyweg–Almudj area was desecrated and there was a high potential for contamination of the Ramsar listed wetlands. The World Heritage Committee intervened, but in 1999, the Australian Government refused to comply with a proposed 18-month stay on mining at Jabiluka [9], during which time the company had to prove how it could proceed without damaging Mirrar cultural values.

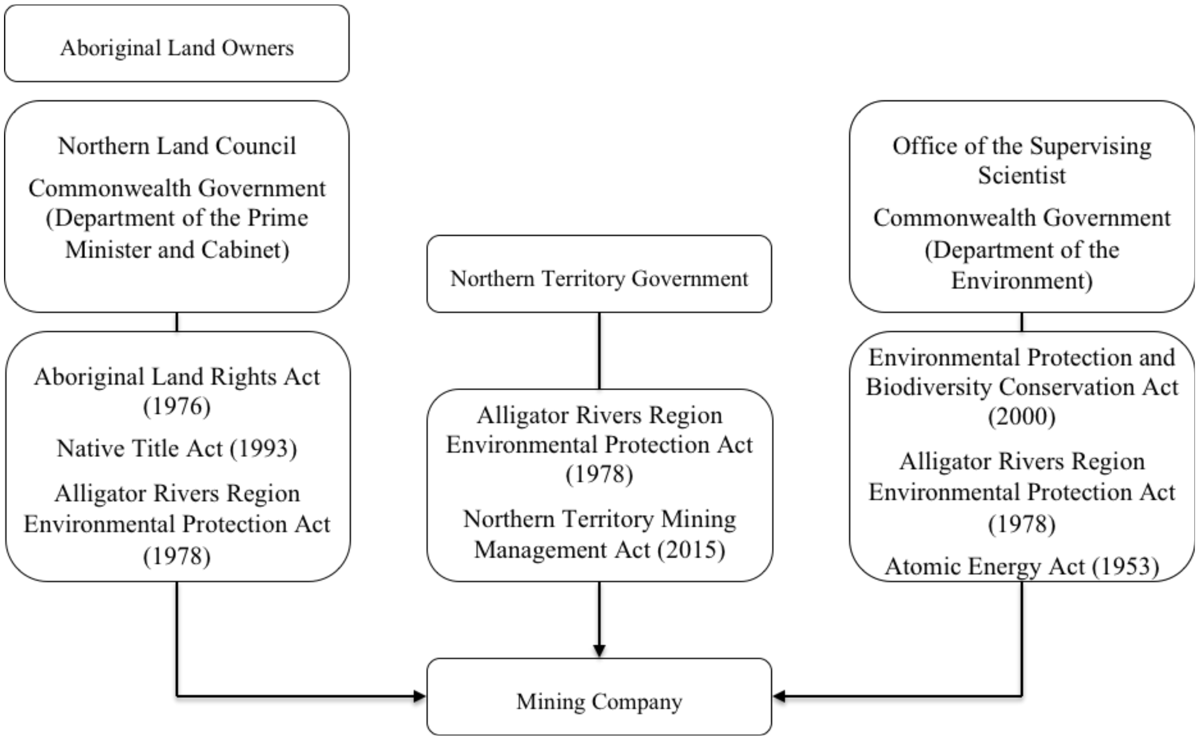


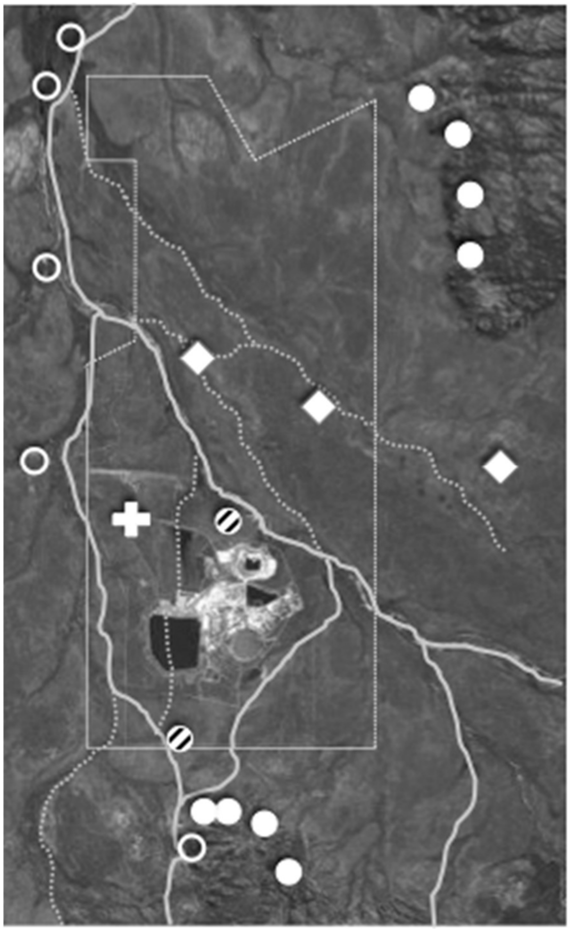
FIG. 2. Schematic representation of legislation impacting the engagement process at Ranger Uranium Mine (reproduced from [11] with permission).

Although Jabiluka entered a 'care and maintenance phase' in 2005, operations continued at Ranger against a backdrop of ongoing but problematic engagement. By 2007, management of the Ranger mine had begun to seek ways to involve Mirrar–Gundjeih'mi in the process of closing the mine. At that time the relationship was poor, so the Northern Land Council, which had acted as an intermediary since the mine's inception, began to work with Mirrar–Gundjeih'mi to develop strategies that ensured cultural requirements would be met when the mine was closed. The first step was to understand how Mirarr viewed the impact Ranger was having upon their lives, how the impact was being managed and what Mirarr thought could be done in the future [10].

In response to Mirarr concerns, strategies around the application of traditional environmental [11] and cultural knowledge [12] were designed to meet certain environmental requirements related to the United Nations Educational Scientific and Cultural Organization's (UNESCO) World Heritage listing for Kakadu National Park that were specified in the mining authorization [13]. In summary, these requirements oblige the mine's managers to ensure that operations at Ranger would be undertaken in a manner such that the attributes for which Kakadu National Park was inscribed on the World Heritage list (Requirement 1.1) would be maintained and that those attributes would not be damaged (Requirement 1.2). In addition, the company is required to rehabilitate the Ranger Project Area to establish an environment similar to the adjacent areas of Kakadu National Park such that the rehabilitated area could be incorporated into the Park (Requirement 2.1).

The natural heritage and cultural attributes ascribed by UNESCO [14] describe the Park as an example of a landscape integrated with cultural tradition of indigenous communities that contains outstanding examples of the hunting and gathering way of life that has dominated Australia since the earliest known human occupation of the continent. These attributes reflect the Mirrar–Gundjeih'mi's continued strong link between spiritual, cultural and physical aspects of the environment. Even though the Ranger Project is considered to be outside of the legislated boundaries of Kakadu National Park, Mirrar–Gundjeih'mi have always recognized it as part of the contiguous environmental and cultural landscape of the Park and, as a consequence, believe the attributes of the Park must also apply to the Ranger Project area. Mirrar–Gundjeih'mi maintain that unless both the natural heritage and cultural attributes are addressed at closure, the mine's operators will never be able to meet its obligation to rehabilitate the mine to the required standard.

Mirrar–Gundjeih'mi were engaged directly and outside of the existing regulatory approach, to determine the key cultural issues that needed to be addressed and included into closure criteria. In keeping with custom, ceremonial and sacred information was not divulged, except where it could be described in high level generic terms. Once incorporated with existing, historical, archaeological and anthropological information, a map of the cultural landscape and the basic requirements for acceptable closure criteria were generated. The map in Fig. 3 shows walking trails, and archaeological, rock art, ceremony, burial and camping sites and demonstrates how the Mirarr–Gundjeih'mi used the pre–mining environment.



Note: The environment was principally used for hunting and gathering and collection of other natural resources of material value. Walking trails are represented by lines, other cultural sites as described below.

Legend

- Rock art sites
- Camping sites
- Archaeological sites
- Ceremony sites
- Burial site

FIG. 3. Cultural landscape of the Ranger Project Area and surrounding parts of Kakadu National Park (reproduced from [12] with permission.

Although it took several more years for mine management to accept the Mirarr–Gundjeih'mi view, progress has been made. Positive outcomes were obtained when this approach was used during rehabilitation at the Boweg–Almudj sacred area [15] and plans for a final landform at Ranger that will more closely match the original landscape than had been previously considered, have been made. Key closure criteria, based upon traditional spiritual perceptions and the cultural values of natural resources that link traditional knowledge with the landform's engineering concepts [11] have been identified and are provided in Table 1. The cultural values of sites will be maintained by the landform design and their context strengthened when culturally appropriate flora species [16] are included.

Throughout the Ranger discussions, it became apparent that if this approach had been adopted prior to mining, it may have been possible to develop a more targeted and culturally appropriate mining operations plan that would have led to improved stakeholder engagement throughout the process and easier progress to closure. Despite the high quality of work that has been undertaken, a level of damage to culture will always remain. However, the outcomes should be of sufficient standard to allow UNESCO to determine if the World Heritage attributes have been damaged and if the goal of maintaining people's connection to the land and their prevailing worldviews has been met.

TABLE 1. HIGH LEVEL CULTURAL CLOSURE CRITERIA FOR THE RANGER URANIUM MINE [11] (REPRODUCED WITH PERMISSION)

Environmental parameter	Key closure criteria	Engineering considerations	Cultural considerations
Topography	Post-mining landform design	Geotechnical stability Erosion Slope Aesthetics Contaminant levels in soil Drainage	Protection of existing sacred and ceremonial sites Re-creation of damaged sacred and ceremonial sites Land use objectives and recreation of natural landscape Access for cultural activities Spiritual implications Sources of food and potable water Sources of traditional medicines and craft materials
Rivers and water bodies	Water quality and human health Water quality and biota health	Water chemistry Ecotoxicology Physical parameters	
Riparian zones	Contaminant levels in arboreal food Correct vegetation patterns, species and removal of weeds	Plant chemistry Biological abundance Biodiversity	

4. TOWARDS A MORE GENERAL STRATEGIC APPROACH

Development of a workable solution for specific problems at the Ranger Uranium Mine generated interest in forming a strategic approach that could be applied to managing cross-cultural engagement at other mines. Commencing 2010, the strategy developed for Ranger Uranium Mine has been applied to a four other Northern Territory mines that had either commenced new operations (Western Desert Resources and Sherwin Iron), or were approaching closure (Bootu Creek and Nabarlek). All four companies were willing to work with the strategy and in all cases, community support was forthcoming.

In each case, the strategy required a degree of modification to compensate for variation in culture across Aboriginal groups, the number of groups involved and the political history behind the project. Consultations allowed identification of several general principles that could potentially be applied across a wider range of mines. From these, a single, basic engagement strategy that integrates alternative worldviews and cultural lores into planning for sustainable environmental and socioeconomic outcomes was drawn. This strategy is shown in Fig. 4.

The strategy was built around the basic principles of free, prior and informed consent; placing a value on alternative worldviews; recognition of Aboriginal rights to land and its management; and the right to participate equally in Australian society while maintaining a separate cultural identity. It requires close cooperation between the company and Aboriginal communities throughout all phases of mining, although both should recognize that some aspects will need to be dominated by the group with the greatest expertise. The best results will be found when cross-cultural discussions are organized according to local custom and driven by the Aboriginal participants in their own language or through the aid of an interpreter. Consultations should cease in response to ceremony and be split where there are significant inter-clan tensions or gender issues that are difficult to resolve.

The key, initial element of the strategy is a cultural risk assessment and formation of cultural management plans which are completed preferably by the affected Aboriginal communities and then integrated into operational and closure plans. All generated outcomes must meet three critical criteria — they must be technically possible, culturally acceptable and economically viable. If any of these criteria cannot be met, then mutually acceptable alternatives must be negotiated, impacted areas excised from the mine or the entire feasibility of the project reviewed.

A second key element involves applying the basic principles to identification of business plans that offer immediate income and long term sustainable outcomes for communities. Ideally, all business plans should be developed in an atmosphere of mutual consent but be integrated with the cultural risk assessment and cultural plans so that cultural integrity is not lost in any drive for economic gain. Where possible, the business plans are linked into mining operations or supported by the mining company. This approach provides Aboriginal people with real equity in project development and an opportunity to guide how their culture is protected from the impacts of mining and any associated business, Aboriginal owned or otherwise. The company benefits from a stronger relationship with Aboriginal communities and, provided capacity exists, decreased cost of response to their business needs.

The strategy is ideally applied prior to mining to ensure strong relationships are built, but may still be applied to mines that are already in operation. It is important that these relationships are built on trust and both parties can be satisfied that cross-cultural communications have been received and understood. However, implementation becomes more difficult the longer mining has progressed, particularly under circumstances where damage to culture or sacred areas has occurred. Difficulties begin to arise where strong, respectful relationships are not in place early or have soured through lack of ongoing engagement.

Development of the strategy has met some resistance mainly because many are reluctant to accept alternative worldviews (which they consider as outside the mainstream of science) and integrate them into mining and closure operations; while Aboriginal people are often reluctant to freely discuss cultural and traditional knowledge. Concerns are also raised about economics, with some criteria considered too restrictive and costly by mining companies and regulators to implement and others perceived to impact unfavorable on profitability of operations. In all four cases where the strategy has been applied, the companies were willing to work with Aboriginal communities to address these concerns and where required, compromises were generated.

Unfortunately, recent economic conditions facing the mining industry have made it difficult to prove the true value of the proposed general strategic approach. Its application to Sherwin Iron and Western Desert Resources was cut short once the companies entered receivership and at Bootu Creek the project was placed into care and maintenance. Work continues at Nabarlek but progress has been slower than anticipated.

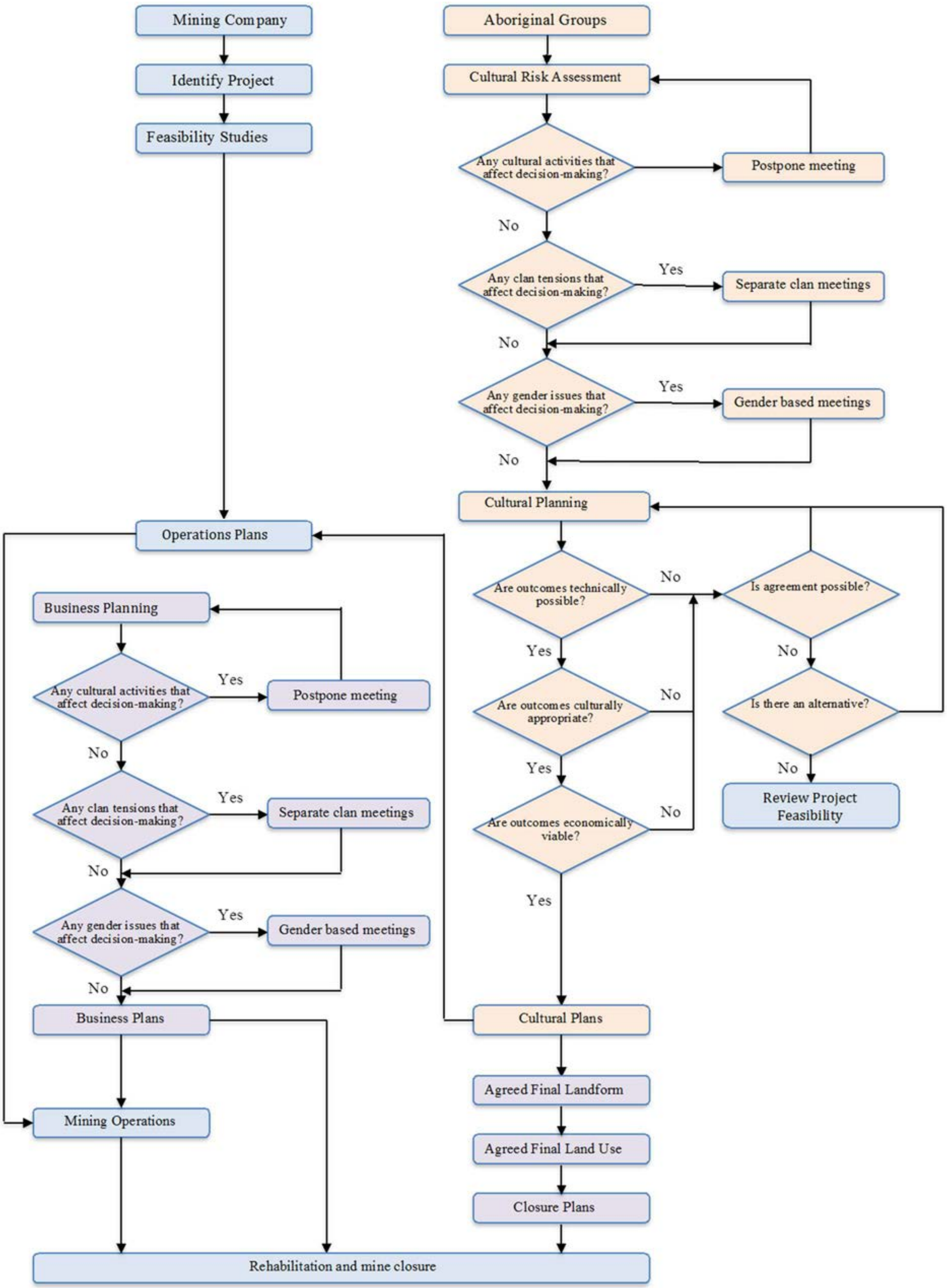


FIG. 4. Schematic representation of general strategy for engagement with Aboriginal people.

5. OUTCOMES AND CONCLUSIONS

Mining company attitudes towards Aboriginal people have changed over the past 50 years from almost total exclusion to full participation. Despite this progress, impacts from significant internal and external politics have had unintended and negative consequences for industry in terms of access to deposits and ease of engagement with the Northern Territory's remote Aboriginal communities. The need for improved systems of corporate social responsibility means that the mining industry is now obliged to attain a 'social license to operate' but must often negotiate this in the face of significant hostility precipitated in part by its past actions.

One important aspect of a company's 'social license to operate' is the ability to successfully negotiate outcomes with all cultural groups affected by mining. Many uranium deposits are in close proximity to Aboriginal communities and, in an era where the quadruple bottom line is of paramount importance to business, improved cross-cultural engagement strategies that allow Aboriginal people to participate in mining operations are necessary. This is best achieved where a deep understanding of alternative worldviews and local political history is developed and successfully employed. By engaging Aboriginal people according to their cultural mores, a workable engagement strategy was developed for the Ranger Uranium Mine and used for resolution of some long standing problems. In turn, this has led to development of a general strategy that may be applicable to the wider mining industry.

This general strategy can be applied to any site and at any point during the life of mine process, but is better employed before mining begins and utilized as operations progress. Early engagement allows stronger and more equitable relationships to be developed, potentially avoiding the need to address damage to cultural sensitivities that may have occurred as a result of ineffective engagement. The strategy has been shown to work during closure planning for the Ranger Uranium Mine, but its effectiveness at other mines has so far been curtailed due to early closure or failure during mine development as a result of poor market conditions. Neither has this strategy been tested under other indigenous nor non–indigenous cultural situations, so further modifications may be required if a truly generic approach to enhanced cross-cultural engagement is to be developed.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the Mirarr–Gundjeih'mi traditional owners for their willingness to share their sacred and traditional knowledge and their experiences with uranium mining; to the International Atomic Energy Agency for providing access to this forum; and to the Northern Land Council for supporting and encouraging this work for the past 8 years.

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19-00381

International Atomic Energy Agency
Vienna
ISBN 978–92–0–103019–1
ISSN 1011–4289