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In Situ Leach Uranium Mining: An Overview of Operations

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IN SITU LEACH URANIUM MINING: AN OVERVIEW OF OPERATIONS

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

In situ leach (ISL) mining, also called in situ leaching or in situ recovery mining, has become a standard uranium production method, following early experimentation and use in the 1960s. Its application to amenable uranium deposits in certain sedimentary formations has grown owing to competitive production costs and low surface impacts. In 1997, the ISL share in total uranium production was 13%; by 2011 it had grown to 46%. ISL mining is expected to remain a major uranium production method for at least the medium term. There has been continual development and improvement of ISL techniques, particularly in the two decades since the IAEA published the Manual of Acid In Situ Leach Uranium Mining Technology, IAEA-TECDOC-1239.

This publication describes how experience with ISL can be used to direct the development of technical activities, taking into account environmental considerations and the economics of the process, including environmental remediation. This report provides an overview of ISL technology and its application. It covers operational experience worldwide for a number of current and past ISL mines, and gives basic descriptions of and notes on the experience gained. With this report, Member States will have more information to design new operations and safely regulate current and future ones with a view to maximizing economic performance and minimizing negative environmental impact.

The IAEA is grateful to all the participants who contributed to this report. The IAEA officers responsible for this publication were J. Slezak and P. Woods of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

This publication has been edited by the editorial staff of the IAEA to the extent considered necessary for the reader's assistance. It does not address questions of responsibility, legal or otherwise, for acts or omissions on the part of any person.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

In situ leach (ISL) mining, also called in situ leaching or in situ recovery (ISR) mining (these terms are considered to be synonomous in this publication), has become a standard uranium mining production method. In this report, ISL mining refers to a special form of solution mining applied to ore deposits in sedimentary, saturated aquifers by using injection and extraction wells from the surface. This report does not include detailed consideration of any kind of leaching in unsaturated formations or of block leaching in underground mine works. In the past, ISL was applied mainly in Bulgaria, the Czech Republic, Kazakhstan, Ukraine, the United States of America (USA) and Uzbekistan. Recently, it has been used in Australia, China, Kazakhstan, the Russian Federation, the USA and Uzbekistan, with small operations or experiments elsewhere.

This publication shows how ISL experience around the world can be used to direct the development of ISL uranium mining activities, with an emphasis on the economics of the process, taking into account environmental considerations including responsible mine closure.

The definition of ISL and associated terms, and the definition of resources and reserves with respect to different schemes are described. The conditions of application and recovery techniques (acid and alkaline leach mining and ion exchange and solvent exchange recovery) are discussed, along with groundwater remediation and above ground decommissioning.

A review of the developments in ISL uranium production is presented in the annexes (annexes to this publication are available on the companion CD-ROM).

This report provides Member States and interested parties with information on how to design and efficiently and safely regulate current and future projects, with a view to maximizing economic performance and minimizing negative environmental impact. Many references are cited that can direct readers to additional information.

1.2. OBJECTIVE

The objective of this report is to show how ISL experience can be used to direct the development of technical activities, taking into account environmental considerations and placing an emphasis on the economics of the process, including the environmental remediation stage.

1.3. SCOPE

This publication deals with the ISL technique of uranium mining as a special form of solution mining applied to uranium ore deposits in sedimentary, saturated aquifers by using injection and extraction wells from the surface. The emphasis is on the establishment and technology of ISL uranium mining, from experimentation, testing, resource quantification and approvals through to operations and closure. Early stage exploration for ISL amenable uranium deposits and detailed geology of deposits are not covered. Historical developments in ISL uranium mining in relevant countries are covered, and the political and social framework is highlighted in case studies from Australia, Kazakhstan and the USA. Fifty-eight historic, current and planned ISL deposits or groups of deposits from around the world are documented, and the future of ISL is discussed.

1.4. STRUCTURE

This publication is divided into seven sections and includes a glossary, conversion factors and a list of abbreviations commonly used in ISL mining literature, as terminology varies around the world.

Following an introduction, resource and reserve are defined in Section 2. International schemes are discussed, and case studies from Australasia, the Russian Federation (also used in some former Soviet Republics and affiliated countries) and the USA are considered in more detail.

Section 3 gives a brief definition of ISL uranium mining and details the conditions of its application. It then describes recovery technology (acid versus alkaline leach, ion exchange versus solvent exchange) and satellite mining. The section finishes with a discussion of groundwater remediation and above ground decommissioning.

Section 4 describes historical and current developments in 13 countries. Information is also provided on individual deposits or deposit groups.

Section 5 considers the political and social framework of ISL uranium mining, with case studies of the regulatory regimes in Australia, Kazakhstan and the USA.

Section 6 provides a compilation of project data (which is expanded on in the annexes), some overall production statistics and the potential for future ISL uranium mining in countries without current or historic experience with the technique.

Finally, Section 7 considers the outlook of ISL uranium mining, its future, key factors affecting its application, economics and markets, technology and environmental management.

The annexes covering 58 individual or group deposits are included on the attached CD-ROM and in the electronic form of the publication only. Where available, annexes list associated company names, location, operational statistics, geology, production technology and parameters, and the restoration approach. These data are incomplete owing to the variable availability of information in the public domain for deposits and mines at different times and in different countries.

2. RESOURCE AND RESERVE DEFINITION

Schemes for the classification of mineral resources, including uranium, have existed for many decades. This has resulted in many differing formal definitions of ‘resource’ and ‘reserve’, and different treatment of economic and other factors, which has often led to great difficulty when comparing uranium and other mineral endowments across the world.

The difficulties in the classification of uranium reserves and resources were the subject of a series of IAEA meetings between 1992 and 1996, which culminated in a publication in 1998 [1]. Rather than dwelling on the history of the subject, this report will concentrate on current international attempts to harmonize reporting and the schemes used in countries producing uranium using the ISL method.

2.1. INTERNATIONAL SCHEMES

The United Nations developed the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC), with versions released in 1997, 2004 and 2009. The UNFC is intended to be a universally accepted and internationally applicable scheme for the classification and reporting of fossil energy and mineral reserves and resources [2, 3]. Currently, UNFC-2009 is the only system that is capable of reporting solid minerals and fluids in the same framework. UNFC-2009 is a generic principle based system in which quantities are classified using a numerical and language independent coding scheme on the basis of three fundamental criteria, which include:

- Economic and social viability;
- Field project status and feasibility;
- Geological knowledge.

Combinations of these criteria create a three dimensional system.

The UNFC has been adopted by a number of uranium producing countries, either officially (e.g. China, India and Ukraine [4]) or informally. The UNFC has a memorandum of understanding with the Committee for Mineral Reserves International Reporting Standards (CRIRSCO), which includes Australasia’s Joint Ore Reserves Committee (JORC), whose scheme is described below.

A draft report to explain the correspondence between the UNFC and codes represented in CRIRSCO was available for public comment in late 2012 [5, 6]. A similar memorandum of understanding also exists with the Society of Petroleum Engineers, the World Petroleum Council, the American Association of Petroleum Geologists and the Society of Petroleum Evaluation Engineers, who co-sponsor the Petroleum Resource Management System, to facilitate bridging with hydrocarbon resources reporting and to provide harmonized generic terminology at a level suitable for global communications.

UNFC-2009 uses numerical coding and avoids commonly used words that are widely misunderstood by non-experts, such as resources and reserves, other than in a general sense. These terms are used with different meanings by the minerals and hydrocarbon industries. UNFC-2009 uses terminology based on project maturity (e.g. commercial projects, potentially commercial projects, non-commercial projects and exploration projects) for defining classes of projects. Further distinction is achieved by an optional use of sub-classes. Because of the unified reporting framework for solids and fluids, UNFC-2009 can adapt to the reporting of ISL projects, where production is somewhat similar to oil and gas extraction, oil shale projects and solid mineral mining.

CRIRSCO, which was formed in 1994 under the auspices of the Council of Mining and Metallurgical Institutes, is a grouping of representatives of organizations that are responsible for developing mineral reporting codes and guidelines including:

- Australasia (JORC);
- Canada (Canadian Institute of Mining, Metallurgy and Petroleum);
- Chile (National Committee);
- Europe (Pan-European Reserves & Resources Reporting Committee);
- South Africa (South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves (more commonly known as SAMREC);
- USA (Society for Mining, Metallurgy & Exploration).

CRIRSCO has published an International Minerals Reporting Code template for the reporting of exploration results, mineral resources and mineral reserves [7].

The definitions of resource categories and their approximate correlation to terms used in major resource classification systems (including Australasia's JORC Code; the National Association for Subsoil Examination (NAEN Code), which is the Russian system also used in Kazakhstan and Uzbekistan, and previously in Ukraine; the USA and Canadian schemes; and the UNFC) are given in the 2011 version of the joint OECD Nuclear Energy Agency and IAEA 'Red Book' publication [8]. The Red Book scheme is summarized in Ref. [8] as follows:

> "Uranium resources are classified by a scheme (based on geological certainty and costs of production) developed to combine resource estimates from a number of different countries into harmonised global figures. "**Identified resources**" (which include *RAR* and *inferred*, see below) refer to uranium deposits delineated by sufficient direct measurement to conduct pre-feasibility and sometimes feasibility studies. For reasonably assured resources (*RAR*), high confidence in estimates of grade and tonnage are generally compatible with mining decision-making standards. *Inferred resources* are not defined with such a high a degree of confidence and generally require further direct measurement prior to making a decision to mine.
>
> "**Undiscovered resources**" (*prognosticated* and *speculative*) refer to resources that are expected to exist based on geological knowledge of previously discovered deposits and regional geological mapping. *Prognosticated resources* refer to those expected to exist in known uranium provinces, generally supported by some direct evidence. *Speculative resources* refer to those expected to exist in geological provinces that may host uranium deposits. Both *prognosticated* and *speculative resources* require significant amounts of exploration before their existence can be confirmed and grades and tonnages can be defined".

In addition, these resources are reported in cost categories. The rationale behind reporting within cost categories is to provide an overview and comparison over time of the relative costs related to the exploration, production and post-production costs associated with the development of the resources. Specifically, Member States are asked to consider the following costs:

(a) Direct costs of mining, transporting and processing the uranium ore;
(b) Costs of associated environmental and waste management during and after mining;
(c) Costs of maintaining non-operating production units, where applicable;
(d) In the case of ongoing projects, non-amortized capital costs;
(e) The capital cost of providing new production units, where applicable, including the cost of financing;
(f) Indirect costs such as office overheads, taxes and royalties, where applicable;
(g) Future exploration and development costs wherever required for further ore delineation to the stage where it is ready to be mined.

In practice, the estimation of the aforementioned costs is not straightforward, and Member States may understand and apply these cost criteria differently in their reporting, particularly when the information required to make these estimates is unknown or not available.

Inputs to the 'Red Book' are overseen by the international Uranium Group, with representatives from countries that produce and that are interested in producing uranium. The 2011 edition notes that UNFC correlation with the OECD Nuclear Energy Agency, IAEA and national classification systems is still under consideration. It can be expected that the various international and national efforts to make useful and intercomparable classification schemes will continue and that new arrangements will be made and adopted over the coming years.

2.2. AUSTRALASIA

2.2.1. The JORC Code

Australasian authoritative guidelines for the statement of resources and reserves are provided by the JORC, sponsored by the Australasian mining industry and its professional organizations. The Code for Reporting of Mineral Resources and Ore Reserves (JORC Code, 2012 edition) [9] is widely accepted as a standard for professional reporting purposes, and is compulsory for companies listed on the Australian and New Zealand Stock Exchanges. This code is also sometimes used outside Australia. A series of terms is defined in the JORC Code, these are both scientifically accurate and take into account mining practicalities, economics and the regulatory setting, also known as 'approvability'. A distinction is made between mineral resources, which are mainly based on the amount of the material of interest in place, and ore reserves, which have had proper consideration of modifying factors: mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors (Fig. 1).

Reports must be authorized by a named, appropriately qualified and experienced practitioner with sufficient experience in the commodity and deposit type involved. This is explicitly defined in the code (ASX in the below quotation refers to the Australian Stock Exchange) [9].

> "A 'Competent Person' is a minerals industry professional who is a Member or Fellow of The Australasian Institute of Mining and Metallurgy, or of the Australian Institute of Geoscientists, or of a 'Recognised Professional Organisation' (RPO), as included in a list available on the JORC and ASX websites."
>
> "A 'competent person' must have a minimum of five years relevant experience in the style of mineralisation or type of deposit under consideration and in the activity which that person is undertaking.
>
> "If the Competent Person is preparing documentation on Exploration Results, the relevant experience must be in exploration. If the Competent Person is estimating, or supervising the estimation of Mineral Resources, the relevant experience must be in the estimation, assessment and evaluation of Mineral Resources. If the Competent Person is estimating, or supervising the estimation of Ore Reserves, the relevant experience must be in the estimation, assessment, evaluation and economic extraction of Ore Reserves."

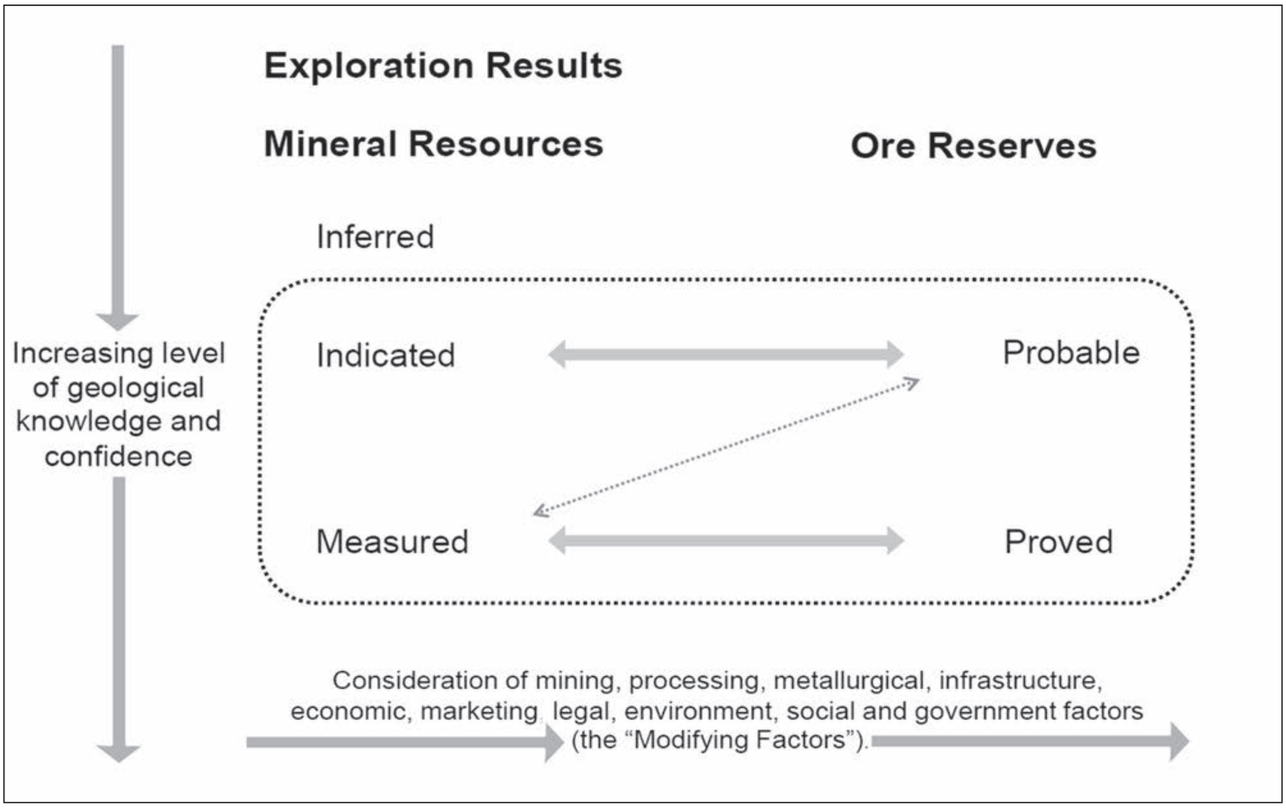

FIG. 1. The JORC Code's general relationship between exploration results, mineral resources and ore reserves (reproduced from Ref. [9]).

The following are brief excerpts from Ref. [9] describing reporting requirements:

> "Exploration Results include data and information generated by exploration programmes that may be of use to investors but which do not form part of a declaration of Mineral Resources or Ore Reserves."
>
> ....
>
> "A 'Mineral Resource' is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade (or quality), and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade (or quality), continuity and other geological characteristics of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge, including sampling. Mineral Resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories."
>
> ....
>
> "An 'Inferred Mineral Resource' is that part of a Mineral Resource for which quantity and grade (or quality) are estimated on the basis of limited geological evidence and sampling. Geological evidence is sufficient to imply but not verify geological and grade (or quality) continuity. It is based on exploration, sampling and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes.
>
> "An Inferred Mineral Resource has a lower level of confidence than that applying to an Indicated Mineral Resource and must not be converted to an Ore Reserve. It is reasonably expected that the majority of Inferred Mineral Resources could be upgraded to Indicated Mineral Resources with continued exploration."
>
> ....

> “An ‘Indicated Mineral Resource’ is that part of a Mineral Resource for which quantity, grade (or quality), densities, shape and physical characteristics are estimated with sufficient confidence to allow the application of Modifying Factors in sufficient detail to support mine planning and evaluation of the economic viability of the deposit.”

....

> “A ‘Measured Mineral Resource’ is that part of a Mineral Resource for which quantity, grade (or quality), densities, shape, and physical characteristics are estimated with confidence sufficient to allow the application of Modifying Factors to support detailed mine planning and final evaluation of the economic viability of the deposit.”

....

> “An ‘Ore Reserve’ is the economically mineable part of a Measured and/or Indicated Mineral Resource. It includes diluting materials and allowances for losses, which may occur when the material is mined or extracted and is defined by studies at Pre-Feasibility or Feasibility level as appropriate that include application of Modifying Factors. Such studies demonstrate that, at the time of reporting, extraction could reasonably be justified.

....

> “The reference point at which Reserves are defined, usually the point where the ore is delivered to the processing plant, must be stated. It is important that, in all situations where the reference point is different, such as for a saleable product, a clarifying statement is included to ensure that the reader is fully informed as to what is being reported.”

....

> “A ‘Probable Ore Reserve’ is the economically mineable part of an Indicated, and in some circumstances, a Measured Mineral Resource. The confidence in the Modifying Factors applying to a Probable Ore Reserve is lower than that applying to a Proved Ore Reserve.”

....

> “A ‘Proved Ore Reserve’ is the economically mineable part of a Measured Mineral Resource. A Proved Ore Reserve implies a high degree of confidence in the Modifying Factors.”

2.2.2. Application of the JORC Code to ISL amenable uranium deposits

The JORC Code was developed with conventional open pit and underground mining in mind. The specifics of ISL mining were considered difficult to apply; this has since been discussed [10] and JORC Code categories of resources (not, to date, reserves, which require a higher level of information, interpretation and confidence) are now reported by some operators. It is typical of ISL projects that mineral resources are quoted in different ways. For example, indicated mineral resources are quoted for the Honeymoon deposit [10], inferred and indicated mineral resources for the Four Mile uranium project [11] and inferred resource only for the Oban project [12]. The Beverley ISL uranium mine is held privately (not listed on any stock exchange) and is not required to report to the JORC Code. In public documents, ‘mineral resource estimates’ are referred to.

2.3. RUSSIAN FEDERATION

The Russian Code for the Public Reporting of Exploration Results, Mineral Resources, Mineral Reserves (NAEN Code) was published in 2011 in both Russian and English [13]. This code was prepared in cooperation with CRIRSCO and the Pan-European Reserves and Resources Committee, based on the CRIRSCO template [7].

The logic of the NAEN Code is that of CRIRSCO, with similarities to other modern codes. Classification is according to the level of geological knowledge and confidence and modifying factors, such as mining, processing, metallurgy, infrastructure, economics, marketing, legal, environmental, social and governmental factors.

The NAEN Code supersedes the previous system and includes guidance on matching of categories. It notes that matching is not mechanical, but requires interpretation on the basis of professional and reasoned judgement by a competent person. The previous system ranked reserves into categories A, B, C_1 and C_2 (progressively less certain) and undiscovered resources into categories P_1, P_2 and P_3 (each with progressively less justification). Earlier variants of this scheme were applied throughout the region. Reporting by this scheme is still required in some jurisdictions.

General discussions on the previous Russian classification scheme, in English, can be found in Refs [14, 15].

2.4. UNITED STATES OF AMERICA

Mineral resource definitions in the USA are chiefly promulgated by the Society of Mining, Metallurgy and Exploration (SME) as published most recently (2014) in Ref. [16]. These definitions are not, however, accepted in their entirety by the US Securities and Exchange Commission (SEC), which regulates public companies registered in the USA. SEC mineral reserve reporting guidelines are published within the SEC series of industry guides [17]. The SEC does not recognize the terms ‘resources’ or ‘inferred’.

2.4.1. SME definitions

Please note that the following definitions are deemed the key elements from both the SME [16] and the SEC [17]. Additional detail is available in each of the publications. The excerpts below are from Ref. [16].

> “31. Exploration Results include data and information generated by mineral exploration programs that might be of use to investors but which do not form part of a declaration of mineral resources or mineral reserves.
>
> Exploration Results may or may not be part of a formal declaration of Mineral Resources and Mineral Reserves.”

....

> “33. A Mineral Resource is a concentration or occurrence of solid material of economic interest in or on the Earth’s crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade or quality, continuity and other geological characteristics of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge, including sampling.
>
> Mineral Resources are subdivided, in order of increasing geoscientific confidence, into Inferred, Indicated and Measured classes.”

....

> “34. An Inferred Mineral Resource is that part of a Mineral Resource for which quantity and grade or quality are estimated on the basis of limited geological evidence and sampling. Geological evidence is sufficient to imply but not verify geological and grade or quality continuity.
>
> “An Inferred Mineral Resource has a lower level of confidence than that applying to an Indicated Mineral Resource and must not be converted to a Mineral Reserve.

....

> “35. An Indicated Mineral Resource is that part of a Mineral Resource for which quantity, grade or quality, densities, shape and physical characteristics are estimated with sufficient confidence to allow the application of Modifying Factors in sufficient detail to support mine planning and evaluation of the economic viability of the deposit. Geological evidence is derived from adequately detailed and reliable exploration, sampling and testing and is sufficient to assume geological and grade or quality continuity between points of observation.

> "An Indicated Mineral Resource has a lower level of confidence than that applying to a Measured Mineral Resource and may only be converted to a Probable Mineral Reserve."
>
> ....
>
> "36. A Measured Mineral Resource is that part of a Mineral Resource for which quantity, grade or quality, densities, shape, and physical characteristics are estimated with confidence sufficient to allow the application of Modifying Factors to support detailed mine planning and final evaluation of the economic viability of the deposit. Geological evidence is derived from detailed and reliable exploration, sampling and testing and is sufficient to confirm geological and grade or quality continuity between points of observation.
>
> A Measured Mineral Resource has a higher level of confidence than that applying to either an Indicated Mineral Resource or an Inferred Mineral Resource. It may be converted to a Proven Mineral Reserve or to a Probable Mineral Reserve."
>
> ....
>
> "38. The words "ore" and "reserves" must not be used in stating Mineral Resource estimates as the terms imply that technical feasibility and economic viability have been demonstrated and are only appropriate when all relevant mining, processing, metallurgical, economic, marketing, legal, environmental, infrastructure, social and governmental factors have been considered. Reports and statements should continue to refer to the appropriate class or classes of Mineral Resources until technical feasibility and economic viability have been established by appropriate studies. If reevaluation indicates that the Mineral Reserves are no longer viable, the Mineral Reserves must be reclassified as Mineral Resources or removed from Mineral Resource/Mineral Reserve statements altogether."
>
> ....
>
> "39. A Mineral Reserve is the economically mineable part of a Measured and/or Indicated Mineral Resource. It includes diluting materials and allowances for losses, which may occur when the material is mined or extracted and is defined by appropriate level of study at Pre-Feasibility, Feasibility, or equivalent, that includes the application of Modifying Factors. Such studies demonstrate that, at the time of reporting, extraction could reasonably be justified."
>
> ....
>
> "40. A Probable Mineral Reserve is the economically mineable part of an Indicated and, in some circumstances, a Measured Mineral Resource. The confidence in the Modifying Factors applying to a Probable Mineral Reserve is lower than that applying to a Proven Mineral Reserve."
>
> "41. A Proven Mineral Reserve is the economically mineable part of a Measured Mineral Resource. A Proven Mineral Reserve implies a high degree of confidence in the Modifying Factors."

2.4.2. US Securities and Exchange Commission definitions

According to the SEC definitions [17], the following apply:

> "(1) Reserve. That part of a mineral deposit which could be economically and legally extracted or produced at the time of the reserve determination.
>
> "Note: Reserves are customarily stated in terms of "ore" when dealing with metalliferous minerals; when other materials such as coal, oil shale, tar, sands, limestone, etc. are involved, an appropriate term such as "recoverable coal" may be substituted.
>
> "(2) *Proven (Measured) Reserves*. Reserves for which (a) quantity is computed from dimensions revealed in outcrops, trenches, workings or drill holes, grade and/or quality are computed from the results of detailed

sampling and (b) the sites for inspection, sampling and measurement are spaced so closely and the geologic character is so well defined that size, shape, depth and mineral content of reserves are well-established;

"(3) *Probable (Indicated) Reserves*. Reserves for which quantity and grade and/or quality are computed form [sic] information similar to that used for proven (measure) reserves, but the sites for inspection, sampling, and measurement are farther apart or are otherwise less adequately spaced. The degree of assurance, although lower than that for proven (measured) reserves, is high enough to assume continuity between points of observation."

3. FUNDAMENTALS OF IN SITU LEACH URANIUM MINING

ISL is a relatively new and increasingly applied method of uranium recovery, which costs less and has a smaller environmental impact in appropriate hydrogeological circumstances compared with other methods of uranium recovery.

3.1. BRIEF DEFINITION

ISL is defined as the extraction of uranium from the host sandstone (in general, sedimentary formations dominated by highly permeable sandstone) by chemical solutions (lixiviants) and the recovery of uranium at the surface. ISL extraction is conducted by injecting a suitable leach solution into the ore zone below the water table; oxidizing, complexing and mobilizing the uranium; recovering the pregnant (loaded) solutions through production wells (extraction wells or recovery wells); and, finally, pumping the uranium bearing solution to the surface for further processing. Some general descriptions are available in Refs [18–20].

In order to reach optimum penetration of the leach solution to the uranium ore, a well defined system of injection and extraction wells (wellfields), both equipped with filter (screen) sections covering the uranium ore horizon, are operated. The geometry of wellfield patterns (regular 5-spot or 7-spot networks, line drives and 'wall' geometries or irregular systems corresponding to specific ore morphologies) and the spacing between injection and extraction wells have to be adjusted to orebody characteristics in order to establish a stable hydrological pumping regime at a suitable flow rate. In order to avoid or minimize the migration of mining fluid into the environment, a bleed from the lixiviant cycle ranging up to a few per cent is usually applied. A network of additional wells around the mining zone is used to monitor and control wellfield performance within the mining horizon as well as in neighbouring formations.

Acid and alkaline leach technologies employ acid and alkaline based leaching systems, respectively. Dilute sulphuric acid is normally used for the former, and carbonate or bicarbonate based leach solutions are used for the latter. Oxygen or hydrogen peroxide is typically added to maintain the strongly oxidizing conditions required to oxidize tetravalent uranium in ore minerals to its hexavalent stage, thus forming uranyl ions (UO_2^{2-}) that undergo complexation either with sulphate or carbonate ions. After recovery of the anionic uranyl (sulphate or carbonate) complexes from the pregnant lixiviant, either by ion exchange, which is predominantly applied, or solvent extraction, barren lixiviant is refortified by dosing the above chemicals in a controlled manner, thus forming a continuous lixiviant recycle. The total amount of mining fluid (lixiviant) in the lixiviant cycle for a given wellfield operation is mainly determined by the (effective) pore volume available for fluid transport in the mineralized aquifer.

3.2. CONDITIONS OF APPLICATION

The following conditions must be fulfilled to apply the ISL method of mining uranium:

(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) A disposal system for wastewater and other residues.

Some experiments or operations only partly satisfy conditions 1 and 4, requiring special considerations and adaptations to the common ISL technologies described in this publication.

ISL for uranium recovery is usually applied to ores confined to water saturated sandstone aquifers of variable consolidation. The water head above the filter sections of the injection/extraction wells (located at the depth of the orebody) need to be sufficient to establish a stable hydraulic regime for wellfield performance. ISL mining has been attempted for sandstone hosted uranium ore bodies close to the ambient water table or in the (unsaturated) vadose zone above it by artificially raising the water table. However, the absolute majority of ISL amenable deposits are, and have been, mined by wellfield applications well below the water table. Exceptional applications of uranium leaching in underground mine works (referred to as block leaching) are not considered in this publication.

The (sedimentary) host formation of the uranium ore needs to be permeable enough to provide a quantitative flow rate from injection to extraction well within the wellfield pattern. Since the flow rate is dependent on several additional factors (hydraulic head, thickness of ore zone, well construction details), there is no definite permeability limit. As a rule of thumb, permeability of the order of 1 m/d (1.2 darcy) or higher is advantageous. Usually, ISL becomes unfeasible at values of the order of about 0.1 m/d and less.

ISL mining involves the extensive recycling of lixiviant, as only a limited proportion of the uranium is mobilized with each pass of the mining solution (determined by the leachability of the ore, i.e. the kinetic rate of uranium mineral dissolution). Mining solution may be pumped through a particular portion of ore 50–100 times, or sometimes more, over a period ranging from a few months to two or more years in length, to achieve the target recovery.

An ore body normally occupies only part of its hosting aquifer, which by its nature is typically in semiconfined to confined aquifer conditions. Mining solution control and environmental protection are easier to achieve where the hydrogeology of the deposit and the surrounding geological formations allow for effective confinement of mining solutions, commonly between impermeable clay rich strata (aquitards). Alternatively, the anisotropy of permeability in larger aquifer formations may be sufficient to control the mining fluid within the mining zone.

The kinetic rate of uranium dissolution (leachability) needs to be high enough for quantitative (economic) ISL performance. This condition is usually met in rather clean sandstones with uraninite or coffinite as the predominant uranium minerals. However, uranium leaching could be constrained or even inhibited in complex mineral matrices, in particular in the case of high abundances of sulphide minerals (e.g. pyrite) and/or carbonaceous material (organic matter). In the case of acid ISL, a high mineral concentration of calcareous material (calcite, aragonite and other carbonates) retards the decrease of pH considerably. This can also cause clogging by precipitates such as gypsum, and could result in non-economic ISL conditions. There are typically two main sources of wastewater from an ISL operation:

(1) Bleed water due to the slightly negative water balance within the lixiviant cycle for wellfield control;
(2) Wastewater from downstream processing of uranium (typically both supernatant from uranium precipitation and wash water used to remove dissolved impurities from uranium concentrate).

Whereas these wastewater categories are (partially) recycled (optionally after treatment) for processing, there is a relatively small quantity of wastewater that cannot be recycled and requires disposal. This is usually by injection into deep, saline aquifers; return to an area of the mined aquifer; or treatment and release or reuse, depending on the local circumstances. Evaporation may be used to reduce the volume to be disposed of. A viable and properly authorized means of wastewater disposal is needed for mining. In the case of water treatment, solid or semisolid waste disposal would normally be necessary. Similarly, there are relatively small quantities of solid low level radioactive waste generated by mining and processing operations for which a viable and properly authorized means of disposal is required. This is typically shallow burial to the requirements of the country where the deposit is mined.

3.3. RECOVERY TECHNOLOGY

3.3.1. Acid versus alkaline leach

Both sulphuric acid and alkaline (carbonate) leaching are used in ISL projects internationally. For both acid and alkaline processes, uranium is usually recovered from the leach solution by ion or solvent exchange, followed by downstream processing including uranium precipitation, thickening, washing, de-watering, drying and packaging (in some cases with additional purification stages).

The main criteria for choosing between acid or alkaline leaching reagent include:

(a) Composition of the host rock and the ore;
(b) Reagent cost and consumption;
(c) Uranium recovery and leaching intensity (residence time and uranium concentration in recovered solution);
(d) Environmental considerations (e.g. aquifer quality and connectedness to other aquifers) and regulatory requirements.

Usually, the most important factor is the abundance of carbonates in the ore zone. For economic leaching using sulphuric acid, the carbonate content in the ore should be less than about 2%. Ores containing higher carbonate concentrations would normally require alkaline leaching. If there is a social or regulatory requirement for active aquifer remediation, alkaline leaching has been found to require less remediation than acidic leaching and is sometimes preferred for this reason. For many acid ISL sites, restoration of groundwater quality is less stringently regulated because of the poor quality of pre-mining groundwater (see Section 3.5 for a discussion on groundwater remediation).

3.3.2. Ion exchange versus solvent extraction

There are two main pathways for the further recovery and processing of uranium extracted in mining solution: ion exchange and solvent extraction, or potentially a combination of the two.

Both uranyl sulphate complexes (from acid leaching) and uranyl carbonate complexes (from alkaline leaching) are anionic and can be easily adsorbed either by ion exchange resins or solvents. The applicability of ion exchange resins could be constrained or even unfeasible owing to high concentrations of competing anions, in particular chloride (in the case of ISL operations in highly saline aquifers). Where the chloride concentration in the lixiviant is sufficiently low, ion exchange is usually the preferred method for selectively removing uranium from the loaded mining solution. The type of anionic ion exchange resin needs to be carefully selected for the given chemical conditions to give the best efficiency (usually based on test work and, in some cases, model based process simulation). Over the last two decades, ion exchange resins have been developed to be effective at chloride concentrations in the lixiviant of up to about 5 g/L. In a separate processing stage, the adsorbed uranyl complexes are eluted from the loaded resin by applying highly ionic eluants (typically nitrate, chloride or other solutions chemically conditioned for best recovery) at a molality of about 1 mol/L or more.

Where salinity and chloride concentration is high from naturally saline aquifers, solvent extraction is the more economical alternative. Solvent extraction is a technology used at many hard rock uranium mines where uranium is first leached from crushed ore. Loaded aqueous mining solution is mixed with an organic phase, typically a form of kerosene with complexing agent(s) such as amines. Uranium complexes transfer selectively to the organic phase. The aqueous and organic phases are allowed to separate under gravity and the mining solution is reconditioned and reused. The organic phase is separately reacted with a second aqueous elution solution (eluant), and the uranium transfers to the second aqueous phase again at higher concentration.

Caution needs to be taken, as the injection of trace organic liquids into an underground regime, be it the recirculation of process waters, may create significant difficulties for groundwater restoration/remediation. Pilot testing of this process should be considered mandatory where active remediation is planned.

In both cases, the final, high grade aqueous uranyl solution (eluate) is treated with further reagents such as peroxide or ammonia to precipitate the uranium as solid phase (uranyl peroxide from hydrogen peroxide precipitation and ammonium diuranate from ammonia precipitation). Calcium and magnesium precipitation and other methods have also been used. This uranium concentrate is then thickened, rinsed to reduce soluble salts such as chlorides and then dewatered and dried to form yellowcake. In some cases, the yellowcake may be further calcined in a furnace to produce uranium oxide or to remove hydrated water from the solids. In all cases, the final product is drummed for sale.

3.4. SATELLITE MINING

Satellite mining refers to the extraction of uranium at a location away from the main treatment plant and its partial processing at that site, for example, to the stage of uranium loaded ion exchange resin. Loaded resin is then transported to the main processing plant for elution and further processing to a saleable product. This process has been used in Kazakhstan and the USA for some years and was recently introduced in Australia [21]. Sometimes a later stage intermediate product may be produced that is then transported for final processing at another plant (e.g. in Uzbekistan).

Factors to be taken into account when deciding if satellite mining is advisable include:

- The distance between proposed satellite mining area and the main treatment plant;
- The precautions required to minimize environmental risks, such as those due to possible vehicle accidents or the crossing of water courses, or effects on environmentally or socially sensitive areas;
- The routes available for the transport of uranium loaded resin, including the additional authorizations, if any, are required if public roads are to be used;
- The supervision requirements of a satellite plant.

Local environmental or social factors as well as costs and logistics may also affect a decision on satellite mining.

3.5. GROUNDWATER REMEDIATION

Remediation[1] (and in some cases disposal) of residual mining solution that remains in the mined aquifer at the completion of mining may or may not be required depending on the following:

- 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;
- The likelihood of migration of residual mining or disposal water.

The need 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 non-governmental organizations. Where remediation is required, the target water quality is also a point of discussion related to whether it needs to meet a given use category (e.g. suitable for stock or domestic water supply, with or without further treatment) or be returned to (or close to) the original water quality within certain ranges.

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[1] As defined in the IAEA Safety Glossary [22] and relevant articles in section 5 of the IAEA Safety Standard GSR Part 3 [23], with regard to radiological protection, some older ISL mining sites can be treated as an existing exposure situation, for which the term remediation can be used. However, some new or younger ISL mining sites should be considered as planned exposure situations. For these cases, restoration may be a better word, although this may have different connotations with regard to non-radiological contaminants and so it is not used here.

Situations in which groundwater remediation is more likely to be required based on scientific, regulatory or social aspects include:

- Groundwater in the aquifer targeted for mining is used by others in the targeted area or 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 required based on scientific, regulatory or social aspects include:

- 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 groundwater is used but 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 owing 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 with 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.

Where remediation is planned or undertaken, various methods are available. The choice of method is likely to be highly site specific, and is highly influenced by the desired or required outcome. Some techniques that have been used or proposed, sometimes in combination, include:

- Cleaning mining fluids via reverse osmosis or other desalination technologies;
- Cleaning mining fluids by ex or in situ precipitation with reagents;
- Injecting a mining zone with a reagent to counter induced acidity/alkalinity;
- Injecting a mining zone with a reagent to induce chemically reducing conditions;
- Washing or flushing a mining zone with formation water (groundwater flush) to reduce the concentration of undesired ions;
- Deliberately drawing mining solution through an adjacent unmined formation to consume acidity/alkalinity and cause the precipitation of metals by reaction with natural components of the aquifer substrate;
- Creation of a reactive in situ neutralizing barrier down gradient of the affected groundwater that will speed the neutralization of mining solution as it passes through the barrier.

For some operations in the USA, a demonstration of the effectiveness of the proposed remediation method on trial mining (field leach trial) is required before permitting full scale operations.

The method of monitored natural attenuation is sometimes considered a ‘do nothing’ approach. Properly applied, this is not the case, as monitoring is required, perhaps in the long term, to establish that sufficient natural attenuation is occurring in a reasonable time frame to give assurance that the desired or required outcome will be reliably achieved. Some form of monitoring is also required for all the active remediation approaches. With active intervention, the timeframe of post-closure monitoring might be reduced compared with unassisted natural attenuation. In some cases, an initial intervention by groundwater flush to kick start natural attenuation (enhanced natural attenuation) has been considered and modelled [24, 25].

Some studies regarding groundwater remediation of ISL projects, either as part of a planned operation or as a later governmental cleanup, are given in Refs [26–36].

All production wells and operational monitoring wells not required for ongoing monitoring should ideally be appropriately decommissioned at the end of mining (or progressively decommissioned) to avoid the possibility of cross-aquifer contamination. At some sites, the sealing of uncased exploration boreholes can be an issue and cross-aquifer contamination can occur if uncased boreholes are not self-sealing, owing to expanding clays [37]. Even where self-sealing of uncased boreholes is considered to occur, cementing to the water table or the surface may still be advisable as a precaution, or may be required by the regulator (e.g. Beverley mine, Australia [38]).

3.6. ABOVE GROUND DECOMMISSIONING

While the emphasis on remediation of ISL mines is often centred on the need or otherwise for groundwater remediation, be it active or passive, above ground components and disturbance of ISL mines also require final decommissioning and possibly remediation appropriate to land use and local regulations [39, 40]. Particular to this need, it is best to immediately remediate surface spills of mining solutions in order to minimize future problems.

4. HISTORICAL DEVELOPMENTS OF IN SITU LEACH MINING

The ISL mining of uranium commenced in the 1960s in the former Soviet Union, Bulgaria, Czech Republic, and the USA. All of these areas witnessed modest application of the technology by the late 1970s, before development stagnated for several decades owing to low uranium prices. The dissolution of the former Soviet Union in 1991 opened the door to western investment in central Asia. Price increases in the early 2000s spurred a rapid increase in investment and subsequent increased production. The following paragraphs set out the historical development of ISL on a country-by-country basis.

4.1. AUSTRALIA

Australia has significant uranium ISL potential associated with palaeochannel, tabular and roll front deposits. Pilot scale testing has been completed at four sites, three with acid extraction chemistry, in Beverley, Honeymoon and Oban in South Australia, and one with alkaline extraction chemistry at Manyingee, Western Australia.

The Beverley and Honeymoon uranium deposits, situated in the Lake Frome Embayment east of the Flinders Ranges in north-eastern South Australia, were discovered in 1969 and 1972, respectively. The mines commenced production in 2000 and 2011, respectively. The most important discovery was in 2005, in Beverley Four Mile, which is the largest known ISL amenable deposit in Australia to date. See Refs [41–44].

4.1.1. Beverley

The Beverley deposit in South Australia was discovered in 1969 by the Oilmin-Transoil-Petromin group of companies. The following year, potentially economic uranium grade was first intersected. Although early plans involved an open pit, this was soon changed to ISL. After further investigations and under the then prevailing political and uranium market circumstances, the project was put on hold. It was sold to Heathgate Resources in 1990.

The deposit, as originally discovered, consists of three main ore zones — north, central and south, in sandy palaeochannels in the otherwise clayey Eocene Namba Formation. In 1996 and 1997, hydrogeological pump testing was completed, and a field leach trial using acid leach and ion exchange technology began in January 1998 after approvals were received. The trial tested mining patterns in the northern and central ore zones for about six months, with good success in both zones. After consideration of an environmental impact statement (EIS), commercial mining of the Beverley uranium deposit was licensed in 1999 and the mine was officially opened in 2001.

Prior to mining, the total initial in place resource was stated to be 21 000 t U_3O_8 (18 000 t U), of which the total resources recoverable by ISL were reported as 16 300 t U_3O_8 (13 800 t U). However, considering the uranium market and both external and internal economic conditions for ISL over the first decade of production, Heathgate Resources put under leach 5 Mt of the Beverley ore with an average grade of 0.22% U_3O_8 (~0.19% U), corresponding to a total resource of 11 000 t U_3O_8 (9300 t U). Total production was 7356 t U_3O_8 (6238 t U) by the end of 2010. Production continued past this time, but the emphasis of production moved to the satellite mines at Beverley North using the Beverley processing plant.

The Beverley North deposits were discovered in 2009 on leases owned by Heathgate Resources, north of Beverley. They occur in the Tertiary Eyre Formation, stratigraphically below the Beverley deposits in the Eocene Namba Formation. In early 2011, after approvals and a successful field leach trial at the Pepegoona orebody, the satellite mining of the Beverley North deposits commenced, in parallel with the mining of the Beverley wellfields. The technology is similar to that at Beverley, with some important adjustments to the chemistry of the leaching solution. Two satellite plants were established, Pepegoona and Pannikan. Loaded ion exchange resin was trucked approximately 15 km to the main Beverley treatment plant and regenerated resin was trucked back to the satellite plants for reuse. Published resources (early 2011) report the production of 4000 t U_3O_8 and 2100 t U_3O_8 (3400 t U and 1800 t U) respectively, although further drilling was undertaken after these figures were published. By 2012, the majority of Heathgate Resources' production was from Beverley North. See Refs [45–54].

4.1.2. Four Mile

The Four Mile uranium deposit was discovered in a drilling programme in 2005, and is located west of the Beverley uranium mine, close to the eastern margin of the Flinders Ranges, in north-east South Australia. Two major sections were recognized, Four Mile East and Four Mile West. Mineralization at Four Mile East is considered to be in the Eyre Formation, as at Beverley North, while mineralization at Four Mile West is considered to be hosted in cretaceous sediments (Bulldog Shale equivalent). The Four Mile East and Four Mile West deposits are estimated to contain resources of 13 000 t U_3O_8 and 19 000 t U_3O_8 (11 000 t U and 16 000 t U) respectively, in the Australian inferred and indicated confidence categories. After the Public Environment Report and other applications were considered, the environmental and other approvals were received in 2013.

The Four Mile deposits are mined as satellites to Beverley using acid leach and ion exchange technology. Four Mile East commenced production in 2014 via the Pannikan facility (Beverley North). See Refs [11, 55, 56].

4.1.3. Honeymoon

The Honeymoon deposit, also in South Australia, was discovered in 1972 and delineation drilling continued until 1976. The uranium mineralization is located in the Yarramba palaeochannel (Eyre Formation), which consists of three or more distinct aquifer sand layers separated by thin, discontinuous clay layers. The lower sand contains the uranium deposit; the upper aquifer is used elsewhere by farmers for stock water.

A first series of ISL trials was carried out at Honeymoon in 1977 and 1979. These trials, together with laboratory tests, confirmed that the deposit would be amenable to ISL mining. In 1982, a demonstration pilot plant (with four 5-spot well patterns) was constructed and a field leach trial began using sulphuric acid and ferric sulphate and using solvent extraction technology. As was the case at Beverley, continuing development was stalled by the Australian Government's earlier 'three mines' uranium policy. The project was placed on care and maintenance in 1983.

Compared with ISL amenable deposits in the USA, the deposit has several different features that are relevant to the use of ISL, including a high pyrite content of 5–15% and high groundwater salinity. The high salinity led to the choice of solvent over ion exchange technology, also in contrast to Beverley. Some limited direct hydraulic connections are interpreted between the subaquifers in the palaeochannel due to gaps in the clay confining layers, although mining solution was maintained in the ore zones during operations.

A new trial at Honeymoon was undertaken in April 1998. A draft EIS was completed in June 2000 for a proposed 850 t U/a facility and approved in late 2001. Following a reassessment, the project moved into development in 2007 with a revised plan to produce 400 t U/a. After a change of ownership the mine was constructed, and production began in September 2011. Owing to low uranium prices, in November 2013 the then owner, Uranium One, announced that the project was to be placed in a status of care and maintenance. See Refs [57–64].

4.1.4. Oban

Also in South Australia, about 60 km north of the Honeymoon deposit, the Oban deposit was discovered in the early 1980s. It is described as a discontinuous roll front type within palaeochannel sands with uranium mineralization at depths of 80–90 m, hosted by a lower sand member of the Eocene Eyre Formation with lignitic, pyritic and carbonaceous characteristics. Oban is estimated to contain 2100 t of eU_3O_8 (1780 tU) within an inferred resource of 8.2 Mt of uranium mineralization at an average grade of 260 ppm eU_3O_8.

The then owner, Curnamona Energy, undertook a field leach trial with a view to a future production rate of >200 t/a. Using sulphuric acid, circulation of acidified groundwater commenced in July 2010. Although there was breakthrough of acidified and oxidizing solution, no significant uranium was detected in the first test. In a further investigation, three sonic core holes were drilled south of the initial leach pattern. The presence of uranium in leachable sands was confirmed by analysis of the cores, but the results also showed that lignitic clay hosted a significant amount of mineralization, with poor leachability expected. The core holes were converted to wells and further leach trials were conducted between pairs of wells. As again no significant uranium was detected, the testing was suspended. At the end of 2011, further investigations at Oban, and exploration nearby, continued. See Refs [12, 41, 42].

4.1.5. Manyingee

The Manyingee deposit, located in the northern part of the Carnarvon Basin in Western Australia, was discovered in 1974 by a joint venture led by Total Australia and drilled until 1984. Manyingee is a roll front type deposit hosted in cretaceous palaeochannel sandstones [65]. To evaluate its ISL amenability and solution confinement, a five-month field leach trial and two pumping tests were completed by 1985. The 5-spot test utilized a solution of sodium carbonate and bicarbonate with added oxidants. Test results were disappointing and suggestions were made for improvements [66], but the uranium market situation of the time, and the government policy at both the State and federal levels delayed further development until 2009. In 1988, Paladin Energy acquired the project, which remains under review. See Refs [41, 65, 66].

4.2. BULGARIA

ISL of uranium in Bulgaria commenced in 1967 within the Thracian Basin in the southern part of the country. Orlov Dol was the first deposit to be developed and was followed by the development of a series of other deposits, totalling 15 in all. Production was by means of sulphuric acid leaching with ion exchange concentration. Ultimately, some 14 000 wells were operated in fifteen wellfields with four satellite recovery units and one resin enrichment plant. Loaded resin from the resin enrichment plant was trucked to the conventional uranium mill at Elishnitsa for final recovery, drying and packaging. All uranium production was carried out under the auspices of a State owned Bulgarian enterprise, Redki Metali.

Production peaked in about 1990 with ISL accounting for approximately 70% of total Bulgarian production, some 300 t U/a. High costs and increasing environmental concerns forced cutbacks in production in the early 1990s and, in 1992, all uranium mining and milling in Bulgaria was closed down by government decree. Some small amounts of further ISL production occurred as a consequence of environmental cleanup. Total production from ISL up to and including 1994 was 5175 t U. See Refs [67–72].

4.3. CHINA

China began consideration of ISL in 1970 and conducted small scale tests in Guangdong province until 1979, as well as in deposit No. 381 in Tenchong in Yunnan province between 1978 and 1981.

In the late 1980s, an initial 12-well acid field leach trial was conducted in the sandstone of deposit No. 381 at Tenchong in the Lianjiang Basin. This was followed by a 31-well semi industrial trial which recovered 62% of the available resource. Industrial scale production commenced in 1991 at a rate of 20 t U/a, and production ceased prior to 1999.

Deposit No. 512, Yili Basin, Xinjiang Autonomous Region, China, was discovered at some point in the late 1950s or early 1960s during coal exploration. Additional exploration in the late 1980s identified a series of deposits (Nos 510–512) with resources of the order of 10 000 t U, the largest accumulation of sandstone roll front type deposits in China. Laboratory and field tests on the potential application of ISL techniques to these deposits were conducted from 1987 to 1991. A larger test on 32 wells (5-spot patterns) was conducted in 1992–1994. Following these tests, commercial mining operations (Mine No. 737) commenced in 1995 at an initial rate of 100 t U/a, subsequently increased to 200–250 t U/a. The lixiviant is H_2SO_4 and the oxidant is H_2O_2. In 2002, the production facility was processing approximately 400 m^3/h with an average concentration of 55–60 mg/L uranium with a possible annual production rate of about 200 t U/a.

An ISL mine using alkaline leach is being developed in northern China. See Refs [73–80].

4.4. CZECH REPUBLIC

Sandstone uranium deposits in the North Bohemian Cretaceous Basin were discovered in 1963. Several deposits were identified, but only three were developed. The Hamr and Brevniste deposits were mined by classical underground mining methods.

The ISL method was applied to the Straz deposit and part of the Hamr deposit. All ISL uranium production in the Czech Republic utilized sulphuric acid as a leaching agent. See Refs [27, 28, 39, 81–87].

4.4.1. Hamr

ISL experimental wellfields were operated on the Hamr deposit in parallel with underground mining from 1971 to 1979. Owing to the expanding depression cone of underground mining, it was necessary to stop active leaching. By 1985, leaching solution was extracted from the mine. After uranium stripping, the barren acid solution was injected partly to operated wellfields on Straz deposit and partly to the hydraulic barrier between the two operations. This overbalance at Straz caused dispersion of acid solutions beyond the mining patterns of the Straz deposit. From 1986, pumping was directed to the drainage system protecting the inflow of acid solutions to underground mine works. Uranium stripping from this solution continued with other uranium production. Surplus acid solutions were treated by lime precipitation and chlorination (for ammonia oxidation) and treated water was finally discharged to a small nearby watercourse. The total production by the ISL method at the Hamr deposit was 1541.5 t U.

4.4.2. Straz

ISL pilot plant testing was initiated on the Straz deposit in 1967. The first experimental wellfield was put into operation in 1968. Industrial operations are considered to have started in 1971. Production increased rapidly to a maximum of 770 t U in 1977 and then levelled off at about 600 t U up to and including to 1991. Production began to decline in 1992 and was officially suspended in 1995, although minimal production as a result of remediation was expected to continue beyond 2012.

Overall, the Straz project included 2210 exploration drill holes, approximately 7700 production wells and 35 leaching fields, covering an area of approximately 6 km^2. Total production at Straz was 16 002 t U (at the end of 2010).

Leaching conditions were considered difficult by current international standards, owing to the slow kinetics of dissolution of uranium from the particular ore minerals present and the fact that part of the mineralization occurred in poorly permeable rocks.

Straz is notable in two ways. Firstly, it was directly adjacent to the underground mine Hamr and, as such, it was necessary to establish a water barrier between the two mines in order to keep Straz saturated. This water barrier consisted of 150 injection wells over a 6.9 km dividing line between the two operations. Treated water from the Hamr mine was injected into this line at a rate of 265 L/s, which maintained saturated conditions at Straz, but also exacerbated water inflows at Hamr.

Secondly, a solution of NH_4NO_3 and HNO_3 was used for resin regeneration. Nitrates were not washed from the resin separately; they were slowly washed out during the next sorption cycle to the injection stream.

Nitrates were decomposed by redox reactions and their concentration in groundwater slowly decreased all the time (an example of natural attenuation), therefore they were not the main problem for restoration.

More complicated was the ammonia content as ammonia is practically resistant to any kind of reaction with ore. During the operation of ISL, no specific wastewater treatment technology was used and the whole volume of excess (waste) solutions from the processing plant was added to the injection stream. For current remediation purposes it is necessary to apply complicated (and expensive) methods to remove ammonia from acid groundwater.

The permanent overbalance of leaching solutions resulted in the sizeable dispersion of contaminated acid solution. With regard to the necessity of guaranteeing the quality of drinking water in the upper Turonian aquifer, it was decided to clean the contaminated groundwater by means of a long term remediation project. The remediation technology known as ‘pump and treat’ was used. This water treatment technology is based on a combination of contaminated solution concentration by forced evaporation and neutralization by lime. For remediation, other than pH, the main chemical species of concern are sulphate, nitrate, ammonium, aluminium, beryllium, uranium and iron.

4.5. HUNGARY

The ISL potential of the Dinnyeberki deposit in the Mecsek Mountain area of southern Hungary was tested briefly in 1988 with a single hexagonal pattern utilizing a sulphuric acid solution. The test failed to confirm the amenability of the deposit to ISL owing to very low permeability.

4.6. KAZAKHSTAN

Kazakhstan’s uranium industry was initially developed under the auspices of the former Soviet Union. Pre-1957 exploration by teams in this area focused mainly on hard rock deposits. Subsequently, conceptual models developed during a regional assessment led to the discovery of sandstone type uranium deposits associated with oxidation–reduction interfaces. During this period, the Chu-Sarysu Basin in central Kazakhstan was explored and discoveries were made of deposits potentially amenable to ISL extraction. These early discoveries included the Uvanas and Zhalpak deposits.

During 1970 and 1971, ISL tests were successfully conducted at the Uvanas deposit and continuing exploration resulted in the discovery of additional deposits including Kandjugan, Moinkum and Mynkuduk.

Exploration experience gained in the Chu-Sarysu Basin was applied in the nearby Syr-Darya Basin between 1970 and 1975 with similar results, including the discovery of North and South Karamuran, Irkol and Zarechnoye.

ISL project development proceeded rapidly in the late 1970s and early 1980s under three mining groups: Stepnoye Mining Company, No. 6 Mining Company and Central Mining Company. Stepnoye production operations at the Uvanas and Mynkuduk deposits commenced in 1978. The No. 6 Mining Company began extraction from the Karamuran deposits in 1981 and Central Mining initiated production at Kandjugan in 1982. All production was based on sulphuric acid leaching.

Production continued, more or less, in steady state at these three production centres until 1994 when Kazakhstan became independent. Displacement of the former administrative structure, low uranium prices and a lack of capital led to rapidly decreasing production. Some mines could not even afford to purchase sufficient acid to maintain production. Subsequently, recognition of the low cost nature of Kazakhstani ISL uranium production and its substantial resource base led to increased interest from foreign firms as well as from the Government of Kazakhstan itself. Increasing investment in existing mines resulted in higher output by 2000.

With higher uranium prices seen in the 2000s, new mines began to be developed, including Akdala, Inkai and Moinkum. By 2005, the realization of these higher prices set off a flurry of new development driven by foreign investment which culminated, in 2009, in the elevation of Kazakhstan to the position of the world’s largest uranium producer. In 2012, overall ISL production in Kazakhstan amounted to 20 890 t U. See Refs [88–100].

4.7. MONGOLIA

Uranium deposits potentially amenable to extraction by ISL occur in several geological depressions (closed basins) within the Gobi region of southern and central Mongolia. Most notable among these depressions are Choir and Hairhan. Both have identified uranium resources, and pilot tests for uranium production have been conducted in both. Additional activity is occurring in south-eastern Mongolia.

A US/Russian/Mongolian joint venture was established in early 1994. This joint venture evolved into the current Gurvan Saihan Joint Venture, the ownership of which comprises Denison Mines (70%), the Mongolian Government (15%) and Geologorazvedka, a Russian Federation Government entity (15%).

The Gurvan Saihan Joint Venture initially focused on the Choir depression and conducted a sulphuric acid leach pilot test at the Haraat N-1 deposit in late 1994. This deposit is partially above the water table, a situation which complicates analysis and design of leachate flow. Nevertheless, the pilot test did confirm that uranium could be recovered in potentially commercial concentrations. Further testing was conducted in 1996 on horizons both above and below the natural water table. The tests did not fully perform as designed, however, owing to site complexities relating to leach solution chemistry. Based on these early tests, further tests can be designed to account for site specific conditions affecting leaching performance. Alternative production methods for this deposit are being evaluated to determine optimal approaches for extracting shallow resources occurring above the natural water table.

In the Hairhan depression at the Hairhan deposit, an initial ISR test was completed in 1998 to determine the appropriate leach chemistry and to verify it under actual field conditions. This sulphuric acid test consisted of a single production well surrounded by four injection wells and associated monitoring wells. The test was operated for about fourteen weeks and was terminated with the onset of freezing weather. Test results confirmed the leachability of mineralization at Hairhan.

The Gurvan Saihan Joint Venture continues to explore and evaluate the Hairhan area for potential future development. Ongoing work has included the collection of baseline site and environmental data. A series of pump tests have been conducted to define host aquifer properties and to determine ISR operating parameters. Work is also underway on the design of a semi commercial scale ISR test at Hairhan.

ISL tests (semiproduction tests) were undertaken at Kharaat in 1994 and 1996 and at Khairkhan in 1998.

AREVA has focused its activity in the East Gobi Province, in the south-east of the country. Within a large sedimentary basin, the promising deposit of Dulann Uul was identified. Following exploratory drilling, AREVA completed a series of hydrogeological tests. An ISR test at Dulann Uul commenced in December 2010.

East Asia Minerals reported indications of uranium mineralization in porous sandstones that might be amenable to ISL mining at the Ingiin-Nars project. See Refs [101–104].

4.8. NIGER

AREVA performed ISL related hydrology testing at the Imouraran deposit in the early 2000s, without leaching, but did not proceed with the technology [105].

4.9. PAKISTAN

Uranium deposits potentially amenable to uranium extraction by ISL were identified in the Siwalik sandstone near the village of Qabul Khel in the north-west frontier province of Pakistan. Laboratory testing of various lixiviants was undertaken in the late 1980s and the first field leach trial was conducted in 1990. A second trial was conducted in 1992 and semicommercial operations were initiated in 1995. Initial operations employed NH_4HCO_3 as lixiviant and H_2O_2 as oxidant. The process plant flow rate was 36 m^3/h and the average concentration was reported to be 68 ppm uranium. On this basis, the production capability of the initial plant can be calculated to be approximately 2 t U/a.

In 2009, it was reported that the Shanawa Uranium Mining Project, an ISL mine in the Karak District, would be developed, with production expected to commence in 2010. This project would utilize an alkaline lixiviant and hydrogen peroxide as an oxidant. Reasonably assured reserves were listed as 578 t U and production costs were estimated to be US $92/kg. The project was expected to have a duration of 5 years. The project was briefly put on hold until more funds were allocated in 2011. See Refs [106–109].

4.10. RUSSIAN FEDERATION

Uranium production by ISL in the Russian Federation is a relatively recent process. Nevertheless, the Russian Federation's background and expertise in ISL has a long history as the former Soviet Union controlled a series of significant ISL mines in eastern Europe and central Asia. With the dissolution of the former Soviet Union, the Russian Federation found itself in need of developing its own domestic resources.

The most advanced ISL projects in the Russian Federation are Dalur and Khiagda. Both projects utilize sulphuric acid as a leaching agent. See Refs [110–117].

4.10.1. Dalur

The Dalur project is located in the Dalmatovsky District of the Kurgan Region of the south-central Russian Federation. Dalur is engaged in commercial operation and development of deposits (Dalmatovskoe and Khokhlovskoe) that belong to the Trans-Urals uranium ore province. Its uranium reserves are estimated at 11 379 t U with an average grade of 0.045% U.

Pilot uranium mining was conducted at both the Dalmatovskoe and Khokhlovskoe deposits in 1984–1994 and resumed with intensity in 1997. The main pregnant solution processing facility with a production capacity of up to 1000 t U/a has been in operation at the Dalmatovskoe deposit since 2006.

In 2009 and 2010, Dalur produced 462 t U and 507 t U, respectively. Full capacity of 800 t U/a is expected to be reached in 2018.

4.10.2. Khiagda

The Khiagda project is located in the Bauntovsky District of the Republic of Buryatia in eastern Siberia. The project is based on uranium deposits of the Khiagdinskoe ore field. Uranium reserves of Khiagda are estimated as 26 805 t U at an average grade of 0.05% uranium.

Pilot uranium production by the ISL method was initiated at the deposits of Khiagdinskoe ore field in 1999. Production in 2008, 2009 and 2010 was 61 t U, 97 t U and 135 t U, respectively. Design capacity is due to be reached in 2018; Khiagda would then be producing up to 1800 t U/a.

4.11. UKRAINE

Some roll front type uranium deposits exist in the sedimentary cover of the Ukrainian shield and are suitable for development by ISL. These deposits are located within the Dnieper brown coal basin and several have been developed, including Devladovskoye, Bratskoye and Safonovskoye. Devladovskoye operated from 1966 to 1983, Bratskoye from 1971 to 1984, and Safonovka from 1982 to 1993. The first two have been completely mined out.

Since 2009, the Ingul'skaya mine has operated a block leaching complex, allowing it significantly lower production costs [118]. However, for the purposes of this publication, this is not considered ISL, notwithstanding some similarities.

Leaching solutions at Devladovskoye and Bratskoye utilized a mixture of sulphuric and nitric acids.

In April 2010, the Ukrainian miner VostGOK said it planned to mine uranium at Safonovskoye deposit from the Nikolaev region in 2012, using ISL methods. See Refs [118–126].

4.12. UNITED STATES OF AMERICA

The USA has large resources of sandstone type deposits potentially amenable to uranium extraction by ISL. The industry has evolved significantly over the past half century. Initial development of ISL mining in the

USA occurred in Wyoming at the Shirley Basin uranium project from 1961–1963, by the Utah Construction and Mining Company (UCMC), later Pathfinder Mines Corporation and then AREVA. UCMC experimented with five generations of wellfield design and over 100 patterns using sulphuric acid chemistry. The Shirley Basin ISL project operated on a small scale from 1962–1970 to produce 577 t U; the ISL mine was closed in 1970 and converted to an open pit operation.

From the late 1960s to mid-1970s, rapid development of ISL mining was in progress, principally in Colorado, New Mexico, Texas and Wyoming. By May 1980, a total of 18 commercial and 9 pilot scale projects were either in operation or under active development. Practically all of these sites utilized alkaline reagents such as ammonia or sodium carbonate/bicarbonate. The difficulty of restoring groundwater at ammonia based sites brought a quick shift in emphasis to sodium carbonate/bicarbonate or carbon dioxide based leaching chemistry by the early 1980s.

Despite years of lower production in the late 1980s, ISL mines have gradually increased their share of the uranium market in the USA from about 1.2% in 1975 to as much as 100% in recent years. By 1991, a total of 62 ISL projects had been designed, although only 24 of these sites were commercialized to some degree. There has been no development of a commercial ISL mine using acid chemistry in the USA since Shirley Basin. There were, however, several sites in Texas (Dunderstadt) and Wyoming (Nine Mile Lake, Reno Ranch and Bear Creek) which underwent pilot scale testing of acid ISL.

The best documented US acid ISL project is Nine Mile Lake, near Casper, Wyoming [127]. The project was developed by Rocky Mountain Energy Co. with the assistance of research by the US Bureau of Mines. Because acid systems mobilize significantly more ions than alkaline systems, they have been proven to be cause difficulties for groundwater restoration, as required in the USA. In addition, relatively high levels of carbonates, as are common in Texas deposits, would require large concentrations of acid and, hence, may increase the cost of recovery to uneconomic levels.

Alkaline leaching in the USA assumes two general forms, which utilize:

(1) Chemical reagents such as sodium carbonate and bicarbonate, used primarily in Wyoming and Nebraska;
(2) Mainly gaseous reagents such as carbon dioxide and oxygen, used in Texas.

The difference relates to a higher natural carbonate content in Texas, which can be utilized to complex the uranium (VI) ion. See Refs [19, 128–134].

4.13. UZBEKISTAN

The information given in Section 4.13 is based on Refs [135–141]. Uzbekistan has numerous uranium deposits that host operating or potential ISL mines. Most of these deposits are concentrated within the large central Kizylkum area. They are generally around 300 m in depth and contain uranium ore in several distinct layers. The ore grades vary from 0.03% to 0.70%. Many have a low carbonate content of less than 2.5%, although some deposits are rich in carbonaceous matter (higher than 5%). Various leaching agents are used, with sulphuric acid being the preferred acid. Information on the extent of operational and environmental impacts is not presently available.

Full scale commercial ISL uranium production was first put into operation in 1961 at the Uchkuduk deposit. At present, the ISL mining method is in operation at Beshkak, Ketmenchi, northern Bukinay, Sabirsay, southern Bukinay and Uchkuduk deposits. The deposits are the assets of the Navoi Mining and Metallurgy Combinat (NMMC). They are developed using sulphuric acid leaching systems, except for the Uchkuduk deposit, where from 1983, a weakly acid technological scheme was used. In this system, only oxidized water is used as a leaching agent.

Up to and including 2009, overall ISL production in Uzbekistan amounted to approximately 114 669 t U.

4.13.1. Northern mining district

The northern mining district 300 km north of Navoi was established to mine uranium at Uchkuduk, from 1961, by underground and open pit mines, with ore treated at a central plant in Navoi. Since 1965, ISL uranium mining has been used at Uchkuduk and at Kendykijube. There is also sulphuric acid production in the district (possibly in conjunction with a copper smelter). Resources in the district amount to 51 000 t U.

4.13.2. Zarafshan

Resources in the Zarafshan mining district (also known as the eastern mining district), about 160 km north of Navoi, are 50 000 t U. The Sugraly deposit was exploited by underground and ISL mining between 1977 and 1994, when it was closed. Subsequently, NMMC had a joint venture with AREVA to redevelop the Sugraly deposit with a reported 38 000 t U resources, but this arrangement appears to have lapsed.

The Central Mining District No. 5 at Zafarabad close to Navoi was set up in 1971 by another entity in Bukhara province and became part of NMMC in 1993. It mines the Bukinay group of uranium deposits by ISL methods. Mines include Beshkak, Lyavlyakan, North and South Bukinai and Tokhumbet. District resources amount to 52 000 t U.

4.13.3. Southern mining district

The southern mining district at Nurabad, Samarkand province, was founded in 1964 to mine the Sabirsay uranium deposit by underground methods, which continued to be carried out until 1983, after which ISL was implemented. The project was transferred from a Tajikistan mining company to NMMC in, or around, 1994. Other mines in this district are Ketmenchi (ISL since 1978), Shark and Ulus. Resources in the district amount to 13 000 t U.

4.13.4. Other deposits

NMMC began mining the major new northern Kanimekh deposit, north-west of Navoi. This project cost US $34 million and was expected to achieve full capacity in 2012. It also started building a pilot plant for ISL at the Alendy and Yarkuduk deposits. In 2009, NMMC was to start developing mines at the Tutlinskaya Ploshad and Meilysai deposits, costing about US $30 million. By the end of 2012, NMMC planned to invest US $165 million in upgrades to expand the existing mining and processing capacities, renew the fleet of process equipment and establish new mines. See Refs [136–141].

4.14. SUMMARY

From very modest beginnings in the 1960s, ISL has developed into the uranium mining method of choice in the early 21st century. This development can be attributed to relatively low capital and operating costs as well as to ISL's low environmental impact in appropriate hydrogeological settings. This is regardless of the fact that only a portion of uranium deposits are amenable to ISL.

World uranium production from ISL has increased from 5400 t U and a 12% share of production in 1990, to 25 300 t U and a 46% share of production in 2011. ISL is expected to provide a major portion of future production in the short to medium term and perhaps beyond.

5. POLITICAL AND SOCIAL FACTORS

Uranium recovery, in general, is subject to somewhat stricter regulation in comparison with that for most mineral commodities owing to the added concern of radiation. Radiation is also of significant concern to the general public because of perceived special negative aspects which are not easily understood by non-specialists.

5.1. REGULATORY REGIMES

5.1.1. Australia

The regulatory regime for uranium mining has developed significantly over decades of mining, which has involved the interplay of national and local (state or territory) regulation. The regulatory history of Beverley, Australia's first ISL mine, is outlined in Refs [41, 46, 47].

The first approvals for Beverley were sought under the national Environmental Protection (Impact of Proposals) Act of 1974 via an EIS released in 1982 [142]. The introduction of the Commonwealth Government's Three Mines Policy in 1983 and declining uranium market prices caused the project to be shelved.

After the abandonment of the Three Mines Policy in 1996, an initial field leach trial was carried out in 1998 and a new EIS was released [50] and subsequently approved [143]. A Commonwealth export licence was also required and obtained. A number of local (state level) approvals were also required, including mining leases under the Mining Act and licences under the Radiation Protection and Control Act and Environment Protection Act.

Extensions to the operations at the original Beverley mine and the nearby Beverley North satellite mines were subject to Public Environment Reports [55, 144] under the Commonwealth Environmental Protection and Biodiversity Conservation Act, which succeeded the Environmental Protection (Impact of Proposals) Act. As with the earlier EIS process, assessment was undertaken in parallel by the Commonwealth and the State of South Australia. Day to day regulation is undertaken by the two departments administering state acts. The mine operates under its approved and (since 2008) public Mining and Rehabilitation Program (MARP) [38, 54], covering Environmental Protection and Biodiversity Conservation, and Mining Act and Environmental Act requirements; and Radiation Management Plans and Radioactive Waste Management Plans, covering Radiation Protection and Control Act licence requirements. Reports to the government are made quarterly and presented at meetings, while the annual Environmental Reports (to 2006) or Mining and Rehabilitation Compliance Reports (since 2006), which are reports that evaluate compliance with the requirements of the MARPs, are publically available reports [145].

Annual radiation protection reports are provided to the Government, and those since 2009 are publically available [146]. The mine site is inspected on a regular and ad hoc basis by the State and Commonwealth authorities, with occasional inspections by the IAEA. The operations are audited against the requirements of the MARPs each year, with two successive internal audits, and every third year an external audit. Results of the audits are included in the annual report. The South Australian uranium mines have been subject to a number of special government investigations [147–149], which have resulted in increased reporting requirements or improvement to equipment and procedures.

The history of Honeymoon is also well documented [62, 150]. At Honeymoon, an EIS for the Honeymoon project was first submitted in 1981 [151]. Government approvals to proceed to the next stage of development of the project were granted, and, in 1982, a pilot plant was installed. Before the pilot wellfield and processing plant could be commissioned, there was a change of government in South Australia and shortly afterwards a change in Commonwealth Government. In March 1983, the grant of a mining lease by the state was refused and the project was placed under care and maintenance in the June of 1983.

In May 1997, under new government policies and approvals, the processing plant was refurbished and the pilot wellfield was re-established. New wellfields were developed and new camp and laboratory facilities were constructed. ISL trials commenced in 1999 and uranium ore concentrate was successfully recovered at the plant. The second EIS for the project in 2000 [58], at a planned production rate of 1000 t/a U_3O_8 equivalent, was assessed jointly by the South Australian and Commonwealth Governments and approved in 2001. Development was then put on hold. The ownership of the project evolved, and in 2008, Uranium One announced a joint venture with Mitsui to complete development of the project at a revised planned production rate of 400 t/a U_3O_8 equivalent and with approval of a publicly available MARP [152] and radiation protection plans. A mining lease and the required State licences were obtained as for Beverley [153]. The reporting and inspection regime is similar to that in place for Beverley, and annual reports are made available to the public [146, 153].

Modern ISL trials, such as that undertaken at Oban from 2010, also require approval or at least acceptance from the Commonwealth authorities and approved MARPs and radiation protection plans to go with mining tenure (in the case of Oban, a retention licence) and licences.

To date, ISL mining has only been undertaken in South Australia. While Commonwealth Best Practice Guidelines for ISR (ISL has been mainly referred to as ISR in Australia since about 2007) were published in

2010 [154]. At the end of 2013, other states and territories were yet to receive an application for ISL trials or mining under regulatory regimes.

5.1.2. Kazakhstan

Contracts for exploration, production or both at uranium deposits need to be made between the competent authority (i.e. the Ministry of Industry and New Technologies of Kazakhstan) and the National Atomic Company (Kazatomprom) pursuant to the law of Kazakhstan, dated 24 June 2010, on subsoil and subsoil use [155]. Kazatomprom, as the national operator of the uranium market of Kazakhstan, has a subsoil use right on uranium deposits on the grounds of direct negotiations with the competent authority. Kazatomprom (or an enterprise where Kazatomprom has a participatory interest) carries out uranium exploration, production or both within the contract territory, pursuant to the contract terms.

A subsoil use contract enters into force from the moment of its registration with the competent authority and compulsory issue of a certificate of registration. The contract validity period is divided into a period of exploration and a period of production. The contract may be prolonged upon the agreement of the parties in accordance with the law on subsoil use [155].

The contract territory will be returned upon the completion of the exploration period, except for areas identified as commercial sites. Returned sites need to meet the requirements of State legislation with respect to environmental protection. The enterprise needs to, at its own expense, reclaim the returned territories and other natural sites disturbed as a result of exploration, production or both until they are fit for further use, in accordance with the applicable State legislation and liquidation project approved in orders set out in the laws of Kazakhstan.

Information on subsurface geological structure and mineral resources, geological characteristics of the deposits, the size of reserves, development conditions and different subsurface characteristics, as are included in geological reports, maps and other materials, is owned by the State if it is received at the expense of the budgetary allocations of Kazakhstan, or is owned by the enterprise if received at the expense of the subsoil user.

Upon contract termination, all geological information becomes State owned. The enterprise needs to deliver, cost free, all documents and other material mediums with geological information, including the initial ones, to the authorized State agency on subsurface study and use.

The enterprise needs to submit full information on programme implementation to the competent authority, including a geological report on the results of operation on the contract territory to the authorized State agency on subsurface study and use. The enterprise needs to pay, in due time, all taxes and other compulsory payments, as well as any fines for inefficient use of subsoil or environment contamination, if they have been issued.

The enterprise needs to annually, not later than 30 calendar days before the date of annual working programme approval, submit an annual programme on goods, works and services procurement to the authorized agency of State control of trade and industrial policy. The enterprise is permitted to start production only after the assessment of reserves has been made by the authorized agency on reserves expertise of Kazakhstan.

The enterprise needs to carry out exploration, production or both in accordance with the programme approved by the authorized agency on subsoil study and use. Implementation of the programme needs to begin no later than 30 days after the contract enters into force.

If a uranium deposit that is economically fit for production is identified, the enterprise needs to inform the competent authority and make a report reflecting the reserves calculation, and their assessment, for submission to the authorized agency on reserves expertise. The authorized agency on reserves expertise needs to carry out the State reserves assessment and issue the appropriate documents in the order set by the law on subsoil use [155].

The subsoil user needs to submit to the competent authority a report on balance of reserves for the previous year by 25 March of the year following the reporting year. The subsoil user needs to submit to the competent authority the detailed report on its operation for the previous year by 25 April of the year following the reporting year, along with the reports required to meet licence contract conditions. Statistical, and other, reports on operation need to be submitted to the appropriate State agencies according to the terms and order set out in the laws of Kazakhstan. The competent authority has a right to monitor whether the subsoil user fulfils the terms of the contract, and its representatives may be present during exploration and production.

A measurement of the mineral resources produced on the contract territory is made by the subsoil user in accordance with the norms and rules set by the State system of uniformity of measurement. The means of measurement need to be checked and certified in accordance with the order set by the authorized agency on technical control and metrology.

The contract includes a section on an abandonment fund. The subsoil user needs to submit, to the competent authority for approval, the programmes on remediation with estimated charges until the end of the exploration period or at the beginning of the production period. The remediation programme needs to include removal or liquidation of facilities and equipment used during the operation on contract territory. For financing remediation works, the subsoil user needs to establish the remediation fund in the amount of 1% from the total volume of investments during the exploration period and not less than 1% from operational costs during the production period.

Particular attention is paid to the conservation of resources and the environment. Ecological, sanitation and epidemiological requirements need to be complied with. Compliance with the law on resources and environmental conservation is controlled by the authorized agency on environmental protection.

The regional structures of the Committee of Geology and Subsoil Use annually carry out scheduled and unscheduled inspections of uranium producing enterprise activity. These inspections check the mining operations, development plans and working programmes of the contract. The enterprise needs to open deposits and mine uranium solely on those deposit blocks and in such amounts that are specified by the mining operations development plans for the current year.

Regional structures of the State Committee for Industrial and Mining Safety Supervision, consisting of the Ministry for Civil Defense, Emergencies and Disaster Response of the Republic of Kazakhstan, regularly check the enterprise’s operation for its adherence to the safety of works at dangerous production sites. Due diligence of the enterprises, as well as the unscheduled inspections, are carried out once in three years.

Further legislation regulates and controls uranium production, transport, import and export. This legislation regulates licensing of defined types of activity. The licensing legislation is based on the constitution of Kazakhstan and consists of laws and other regulatory legal acts. The activities subjected to licensing are defined. A licence is necessary for carrying out activities, including:

- Manufacturing, production, storage and processing of nuclear materials and radioactive substances;
- Realization (handling, sale and purchase) of nuclear materials, ionizing irradiation sources and radioactive substances;
- Transport of nuclear materials and radioactive substances, including transiting.

5.1.3. United States of America

ISL uranium regulation in the USA is, in most cases, a complex, lengthy and fluid process that involves the following:

(a) Local, state and federal authorities participating to varying degrees with a significant potential for overlapping jurisdiction;
(b) Non-governmental organizations active in opposition to the licensing process at all levels;
(c) The political process, which can assume a dominant role.

At the highest level, the US Nuclear Regulatory Commission (NRC) maintains the ultimate responsibility for the regulation of the US nuclear industry, including uranium extraction and ISL. This responsibility can be assumed by individual states under strict agreement with the NRC to exercise regulatory authority over this type of material. Those states are termed ‘agreement states’. The US Environmental Protection Agency (EPA) retains ultimate responsibility for underground sources of drinking water (USDW). This responsibility may clash at times with that of the NRC, in particular with ISL projects. From an operator perspective this may contribute to delays, uncertainties and overlaps in the regulatory process. EPA responsibility can also be delegated to, or shared with, individual states resulting in a patchwork of regulatory authority. Table 1 sets forth a listing of primacy for both the NRC and the EPA in selected states with actual or possible ISL uranium mining.

TABLE 1. REGULATORY PRIMACY FOR IN SITU LEACH URANIUM MINING IN THE USA

State	Uranium production	Groundwater protection
Arizona	US NRC	US EPA
Colorado	State	Joint state/EPA programme
Montana	US NRC	Joint state/EPA programme
Nebraska	US NRC	State
New Mexico	US NRC	State
South Dakota	US NRC	Joint state/EPA programme
Texas	State	State
Utah	State	State
Wyoming	US NRC	State

Regulatory processes for licensing ISL uranium production in the USA typically consist of two principal areas of activity, including:

(1) A radioactive materials licence (RML) for the processing facility;
(2) An underground injection control permit for the wellfields.

The application for a RML, either through the NRC or the State, requires a detailed environmental report with a significant degree of focus on hazardous, radiological and cumulative impacts, including air, water, waste, emissions and effluents, as well as personnel and public exposure. The process is reasonably well established and generally founded upon licensing of uranium mills. Regarding satellite ion exchange units, it is not always clear whether each satellite needs to receive a separate RML. A General Environment Impact Statement [156] may streamline the RML licensing process since most processing facilities are quite similar in both design and operation.

Underground injection control permits are more complex since the characteristics of individual deposits may be quite diverse. An aquifer exemption is required in order to receive an underground injection control permit for ISL of uranium. This exemption removes an aquifer from classification as an underground source of drinking water if one of the following can be demonstrated:

(a) It is not a source of drinking water.
(b) It cannot serve as a source of drinking water in the future.
(c) The total dissolved solids value is more than 3000 ppm and less than 10 000 ppm and is not reasonably expected to supply a public water system.

This demonstration process may prove that an aquifer has one or more of the following features:

(1) It contains minerals that are expected to be commercially producible.
(2) It is at a depth or location that makes recovery of drinking water impractical.
(3) It is too contaminated for human consumption.

Wellfield authorizations are typically a two-step process (assuming an NRC licence, and any other approvals) that includes a Class III Well Area Permit and a Production Area Authorization for each orebody or major portion thereof.

The EPA [157] defines a Class III well as a well "used to inject fluids to dissolve and extract minerals." This source goes on to describe Class III well types as follows:

> "Class III wells are used to mine:
>
> - Uranium
> - Salt
> - Copper
> - Sulfur
>
> "More than 50 percent of the salt and 80 percent of the uranium extraction in the United States involve the use of Class III injection wells.
>
> "Uranium in-situ leaching (ISL) is the most common method by which uranium is extracted in the United States. A typical uranium mining operation requires injection, extraction, and monitoring wells. The process includes the following steps:
>
> - Injection wells are drilled into the formation containing the uranium.
> - A solution known as a lixiviant is injected into the mineral bearing rocks. The solution is allowed to remain in contact with the rocks long enough to dissolve the uranium ore.
> - When the lixiviant is almost saturated with uranium, the fluid is brought to the surface via a production well.
> - At the surface, uranium is separated from the lixiviant.
> - The lixiviant is then injected to extract more uranium.
>
> "The majority of Class III wells in the United States are uranium ISL wells."

The EPA provides the following requirements for construction and operation of a Class III well [157]:

> "All Class III wells are operated under individual or area permits. Contamination from mining wells is prevented by implementing requirements for mining well operators. Before injection begins operators must obtain an aquifer exemption when:
>
> - Solution mining fluids are injected directly into a USDW (which is common in ISL uranium mining)
> - Overlying aquifers could subside (a potential occurrence during salt mining)
>
> "Additional owner or operator requirements:
>
> - Construct wells with tubing made of materials that are appropriate for the injected fluids, and cased and cemented to prevent the migration of fluids into a USDW.
> - Pressure test wells prior to injection.
> - During operation, monitor injection pressure and flow rate. Do not inject fluid between the outer-most casing and the well bore.
> - Monitor USDWs below and above the mining interval when solution mining fluids are injected into a USDW of 3,000 parts per million total dissolved solids or less.
> - Test the casings of salt solution mining well for leaks at least once every five years.
> - Properly close (plug and abandon) wells when injection operations are complete."

A Class III well area permit is a permit issued for a defined area that includes:

(a) Multiple Class III wells that are authorized within the defined area;
(b) Wells of similar design and operation;
(c) A single operator for all wells.

A production area authorization is a document issued under the terms of a Class III injection well permit approving the initiation of mining activities in a specified production area within the larger Class III well permit area. Several production area authorizations may be issued under a single Class III well area permit.

Groundwater restoration is a key element in the licensing and operation of any US ISL project. Typically, baseline values are the target restoration values for all established drinking water parameters. Best practical technology needs to be used to meet target restoration values. If best practice technology is unable to meet target restoration values, it may be possible to amend those values so long as the 'class of use' of the groundwater is unchanged. It needs to be emphasized that, at the time of writing, there were no known instances in the USA where groundwater in a uranium deposit met US EPA drinking water standards.

5.2. POLITICAL AND SOVEREIGN FACTORS

In mining in general and uranium mining in particular, including ISL, sociopolitical factors can have a large influence on the discovery, approval timing and conditions, reporting and inspection requirements. In some jurisdictions, uranium exploration is specifically banned; in others, exploration is possible but bans are in place regarding mining. Jurisdictions can also influence uranium mining without actual bans by increasing or decreasing regulatory hurdles or by providing incentives or disincentives.

Sovereign risk is a related concept, and is often used to describe:

- The risk of adverse changes to permissions or conditions after exploration or mining has commenced.
- The overruling of approvals by a higher or lower level of government or in the legal system.
- The possibility of forced nationalization or confiscation of private assets. The latter may be partial or complete nationalization.

The risks of disruption owing to criminal activity, civil war or terrorism might also be considered here, although these are not risks particular to uranium mining or even mining in general.

A consulting company, Ux Consulting, listed external factors that affect both individual projects and companies that undertake uranium mining and extraction in general [118], including:

- Geopolitical factors;
- Regulatory factors;
- Exchange rates.

Mays, in Ref. [158], discusses uranium mining in general, and considers limitation to progress in developing uranium resources to include: "historical overview, price, development of reserves and potential resources, social attitudes, political policies, legal constraints, environmental permitting and licensing, personnel, supplies and equipment manufacturing, financing and technical limitations." Because of the high public profile of mining, and uranium mining in particular as part of the nuclear fuel cycle (with associated nuclear weapons proliferation, nuclear accidents and waste management concerns), political and sovereign risk factors are likely to remain important in the industry in the coming decades.

6. COMPILATION OF PROJECT DATA

6.1. COMPILATION OF PROJECT DATA

A listing of known ISL mines and prospects for which information is available is given in Table 2. Data are provided in the annexes for the indicated ISL projects.

TABLE 2. LISTING OF ISL MINES AND PROSPECTS

Country	Production centre	Principal owner(s) during operations or as of 31 Dec. 2011	Startup year	Nominal capacity (t U/a)	Status as of 31 Dec. 2011	Data sheet
Australia	Beverley (including satellites)	Heathgate Resources	2001	850	Operating	Yes
	Four Mile	Quasar Resources/ Alliance Resources	—	n.a.	Undeveloped	No
	Honeymoon	Uranium One	2011	300	Operating	Yes
	Oban	Curnamona Energy	—	—	Undeveloped	No
	Manyingee	Paladin Energy	—	385	Undeveloped	No
Bulgaria	Belosem/Belozem	Redki Metali	1982	100	Closed	No
	Cheshmata	Redki Metali	n.a.	n.a.	Closed	No
	Chukarevo	Redki Metali	n.a.	n.a.	Closed	No
	Debar/Debur	Redki Metali	1985	20	Closed	No
	Hoskovo/Haskovo	Redki Metali	1977	50	Closed	No
	Isgrev	Redki Metali	n.a.	n.a.	Closed	No
	Madretz/Mudrets	Redki Metali	1974	25	Closed	No
	Manole	Redki Metali	n.a.	n.a.	Closed	No
	Marritza/Maritsa/ Maritza	Redki Metali	1984	10	Closed	No
	Navasan/Navasen/ Navussen	Redki Metali	1978	20	Closed	No
	Okop Tenevo/ Okop-Tenebo	Redki Metali	1986	50	Closed	No
	Orlov Dol	Redki Metali	1969	20	Closed	No
	Plovdiv/Momino	Redki Metali	1975	100/300	Closed	Yes

For footnotes see p. 34.

TABLE 2. LISTING OF ISL MINES AND PROSPECTS (cont.)

Country	Production centre	Principal owner(s) during operations or as of 31 Dec. 2011	Startup year	Nominal capacity (t U/a)	Status as of 31 Dec. 2011	Data sheet
	Pravoslaven	Redki Metali	n.a.	n.a.	Closed	No
	Rakovski	Redki Metali	n.a.	n.a.	Closed	No
	Trilistnik	Redki Metali	1981	10	Closed	No
	Troian/Troyan	Redki Metali	1989	10	Closed	No
	Tsarimir/Tzarimir	Redki Metali	n.a.	n.a.	Closed	No
	Vladimirovo	Redki Metali	1979	30	Closed	No
	Zeretelevo/ Tzeretelovo/ Tseretelevo	Redki Metali	1984	100	Closed	No
China	Tenchong	CNNC	1991	20	Unknown	No
	Yining II (Deposit 512)	CNNC	1994	300	Operating	Yes
	Yining IV (Deposit 511)	CNNC	—	—	Undeveloped	No
Czech Republic	Straz	Diamo	1968	700	Closed	Yes
Kazakhstan	Akdala	Uranium One/KAP	2001	1000	Operating	Yes
	Budenovskoe 1, 3 and 4	Uranium One/KAP	2009	2000	Operating /Dev.	No
	Budenovskoe (Karatau)	Uranium One/KAP	2007	2000	Operating	Yes
	Central Mynkuduk	KAP	2007	2000	Operating	Yes
	Chieli (North and South Karamuran)	Mining Group-6 (KAP)	1985	1250	Operating	Yes
	Inkai	Cameco/KAP	2002	2000	Operating	Yes
	Irkol	KAP/China	2007	750	Operating	Yes
	Kharasan 1	Uranium One/KAP/ Energy Asia	2008	3000	Operating	Yes
	Kharasan 2	KAP/Japan	2009	2000	Operating	Yes

For footnotes see p. 34.

TABLE 2. LISTING OF ISL MINES AND PROSPECTS (cont.)

Country	Production centre	Principal owner(s) during operations or as of 31 Dec. 2011	Startup year	Nominal capacity (t U/a)	Status as of 31 Dec. 2011	Data sheet
	Moinkum/ Tortkuduk	AREVA/KAP	2001	4000	Operating	Yes
	Semizbai	KAP/China	1982/2009	500	Operating	Yes
	South Inkai	Uranium One/KAP	2007	2000	Operating	Yes
	Stepnoye (Uvanas, East Mynkuduk)	Stepnoye (KAP)	1978	1300	Operating	Yes
	Taukent (Kanzugan, Moinkum)	Taukentskiy MCC (KAP)	1983	1200	Operating	Yes
	West Mynkuduk	KAP/Japan	2008	1000	Operating	Yes
	Zarechnoye	KAP/ARMZ (Uranium One)	2007	1000	Operating	Yes
	Zhalpak	KAP/China	—	1000	Proposed	Yes
Mongolia	Dulaan Uul	AREVA	—	—	Undeveloped	No
	Hairhan	Denison	—	—	Undeveloped	No
	Haraat	Denison	—	—	Undeveloped	No
Pakistan	Qabul Khel	PAEC	1995	40–60	Operating	Yes
Russian Federation	Dalur	TVEL	2002	1000	Operating	Yes
	Khiagda	TVEL	2002	1000	Developing	Yes
Ukraine	Bratskoye	VostGOK	1971	—	Closed	No
	Devladovskoye	VostGOK	1966	—	Closed	No
	Safonovka	VostGOK	1982	—	Closed	No

For footnotes see p. 34.

TABLE 2. LISTING OF ISL MINES AND PROSPECTS (cont.)

Country	Production centre	Principal owner(s) during operations or as of 31 Dec. 2011	Startup year	Nominal capacity (t U/a)	Status as of 31 Dec. 2011	Data sheet
USA	Alta Mesa	Mesteña	2006	680	Operating	Yes
	Benavides	Uranium Resources Inc	1980	200	Closed	Yes
	Bison Basin	Ogle Petroleum	1981	175	Closed	Yes
	Bruni	Westinghouse	1975	200	Closed	Yes
	Burns Ranch	U.S. Steel	1977	400	Closed	Yes
	Church Rock	Hydro Resources Inc	—	450	In development	No
	Clay West	U.S. Steel	1975	400	Closed	Yes
	Crow Butte (includes Big Red)	Cameco Resources	1991	450	Operating	Yes
	Crownpoint	Hydro Resources Inc.	n.a.	450	In development	No
	Dewey Burdock	Powertech Uranium Corp.	n.a.	400	Undeveloped	No
	El Mesquite	Cogema (AREVA)	1976	250	Closed	Yes
	Gas Hills (satellite to Smith Ranch/Highland)	Cameco Resources	n.a.	n.a.	Undeveloped	No
	Highland	Cameco Resources	1988	770	Closed	Yes
	Hobson (central plant)	South Texas Mining Venture	—	450	Operating	No
	Hobson – Goliad	Uranium Energy	n.a.	450	Undeveloped	Yes
	Hobson – Irigaray	AREVA	1977	150	Reclamation	Yes
	Hobson – Las Palmas	Everest	1981	80	Closed	Yes
	Hobson – Mt Lucas	Everest	1983	—	—	Yes
	Hobson – Palangana	South Texas Mining Venture	2011	450	Operating	Yes
	Hobson – Palangana	Uranium One	1977	400	Closed	Yes
	Hobson – Tex-1	Texaco/Everest	1986	n.a.	Closed	Yes

For footnotes see p. 34.

TABLE 2. LISTING OF ISL MINES AND PROSPECTS (cont.)

Country	Production centre	Principal owner(s) during operations or as of 31 Dec. 2011	Startup year	Nominal capacity (t U/a)	Status as of 31 Dec. 2011	Data sheet
	Irigaray	Cogema	1977	275	Reclaimed, standby	Yes
	Irigaray/ Christensen (now called Willow Creek)	AREVA	1989	275	Reclamation	Yes
	Jab and Antelope	Uranium One	—	450	In development	
	Kingsville Dome	Uranium Resources Inc.	1988	540	Reclaimed, standby	Yes
	Kingsville Dome – Vasquez	Uranium Resources Inc.	2004	350	Reclamation	Yes
	Lamprecht	Interncontinental Energy Corp.	1977	125	Closed	Yes
	Longoria	Uranium Resources Inc.	1979	75	Closed	
	Lost Creek	Ur-Energy	—	900	Construction	Yes
	McBryde	Caithness Mining Corp.	n.a.	80	Closed	Yes
	Moore Ranch	Uranium One	n.a.	225	Permitted	No
	Nichols Ranch	Uranerz	—	900	Construction	Yes
	Nichols Ranch – Hank Satellite	Uranerz	—	115	Construction	Yes
	North Butte (satellite to Smith Ranch/Highland)	Cameco	n.a.	n.a.	Undeveloped	No
	Pawnee	Interncontinental Energy Corp.	1977	n.a.	Closed	Yes
	Palangana	Union Carbide	1977	100	Closed	No
	Reno Creek	Bayswater/Pacific Road	n.a.	500	Undeveloped	No
	Rosita	Uranium Resources Inc.	1990	575	Restoration, standby	Yes
	Ross	Strata Energy Inc.	—	1360	In development	No
	Ruth	Cameco Resources	n.a.na	200	Undeveloped	No
	Smith Ranch/ Highland	Cameco Resources	1997	2500	Operating	Yes

For footnotes see p. 34.

TABLE 2. LISTING OF ISL MINES AND PROSPECTS (cont.)

Country	Production centre	Principal owner(s) during operations or as of 31 Dec. 2011	Startup year	Nominal capacity (t U/a)	Status as of 31 Dec. 2011	Data sheet
	Sweetwater	Kennecott	n.a.	200	Undeveloped	No
	Trevino	Conoco Inc.	1981	209	Closed	Yes
	Unit One	Interncontinental Energy Corp.	n.a.	400	Undeveloped	No
	West Cole	Tenneco U, Total Minerals	1982	100	Closed	Yes
	West Largo	Uranium Resources Inc	n.a.	400	Undeveloped	No
	Willow Creek (Irigary – Christensens Ranch)	Uranium One	1989, 2011	590	Operating	No
	Zamzow	Interncontinental Energy Corp.	1977	75	Closed	Yes
	Mining Division No. 5 (Zafarbad)	Navoi Mining and Metal	1968	900	Operating	Yes
Uzbekistan	Southern Mining Division (Nuradad)	Navoi Mining and Metal	1966	650	Operating	Yes
	Northern Division (Uchkuduk)	Navoi Mining and Metal	1964	750	Operating	Yes
	Sugraly	Navoi Mining and Metal	1977	n.a.	Decommissioning	No

—: data not available.
n.a.: not applicable.

6.2. ISL PRODUCTION STATISTICS

Figure 2 compares total world production of uranium with ISL production from 1982 up to and including 2010. Table 3 and Fig. 3 summarize historical ISL production by country. It is notable that, up to and including 2010, ISL production accounted for approximately 230 000 t U, or about 10% of the total historical world production. In 2011, the percentage of annual production attributable to ISL reached 46%.

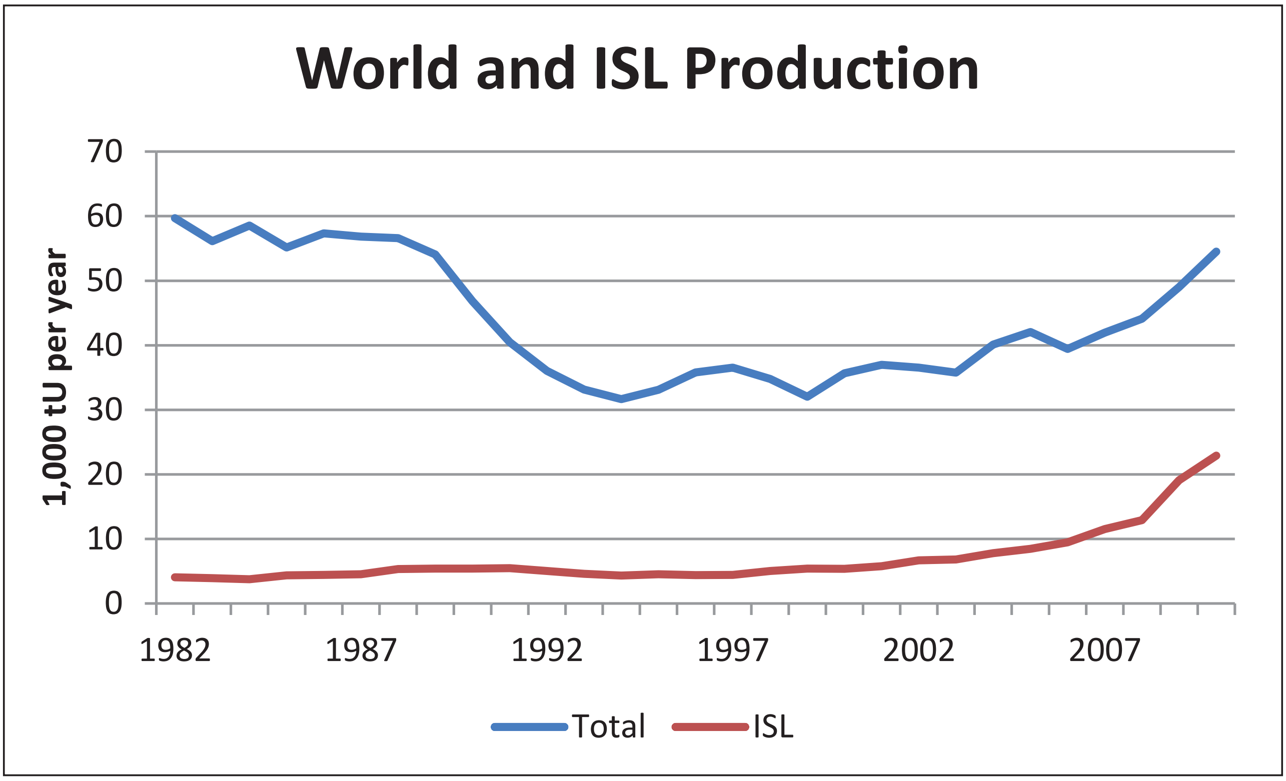

FIG. 2. ISL uranium production versus total world uranium production (data from T. Pool, International Nuclear, Inc.).

TABLE 3. TOTAL ISL URANIUM PRODUCTION UP TO AND INCLUDING 2010 AND ANNUAL ISL URANIUM PRODUCTION IN 2010

Country	Uranium production (t U)	Time period	Annual production of U in 2010 (t U)
Australia	6 200	2000–2010	364
Bulgaria	1 500	1967–1992	0
China	3 700	1991–2010	330
Former Czechoslovakia and current Czech Republic [a]	17 500	1968–2010	18.6
Kazakhstan	95 200	1978–2010	17 451
Pakistan	200	1995–2010	<0.1
Russian Federation	6 300	2006–2010	642
USA	35 300	1962–2010	1 231
Uzbekistan	61 900	1961–2010	2 874
Total	227 700	1961–2010	22 905

[a] The uranium producing areas of the former Czechoslovakia are all now found in the Czech Republic.

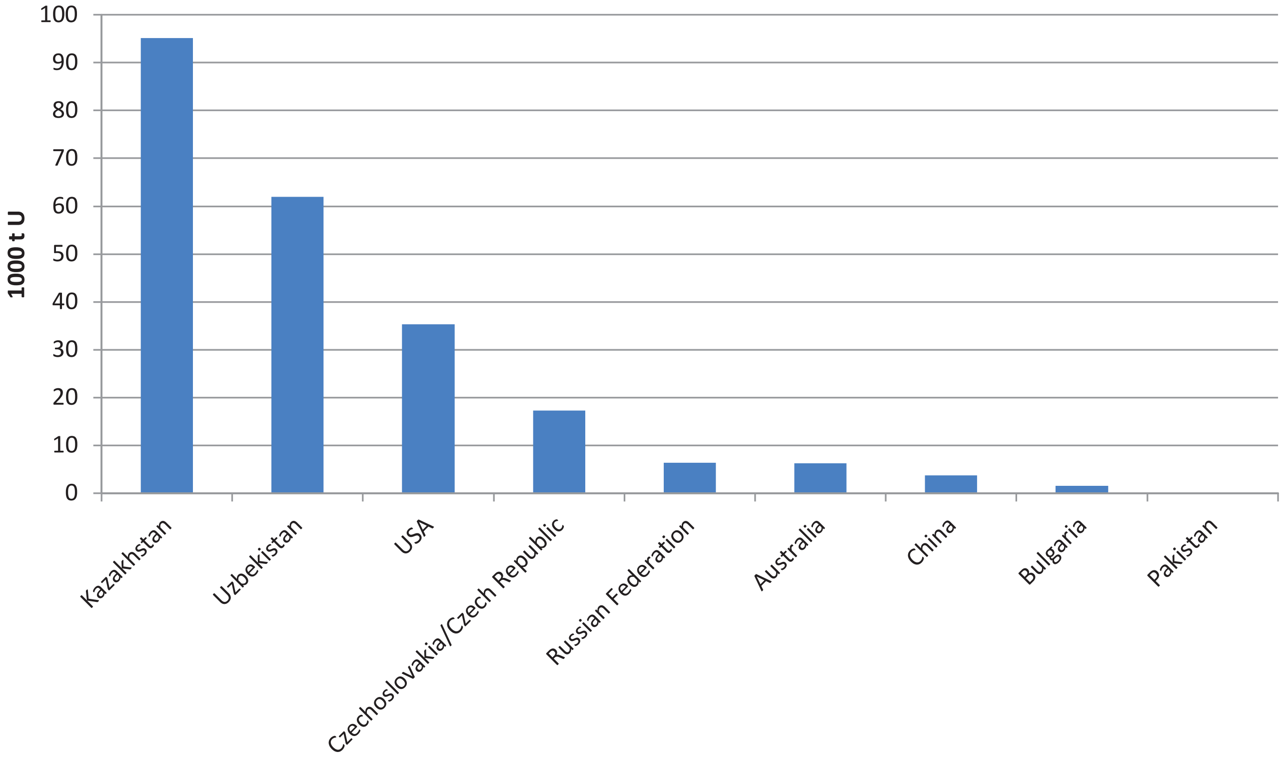

FIG. 3. ISL uranium production (in t U) up to and including 2010 for select countries (data from T. Pool, International Nuclear, Inc.). Data for Czechoslovakia include production in former Czechoslovakia and current Czech Republic.

6.3. POTENTIAL FUTURE ISL COUNTRIES

ISL is potentially applicable for uranium recovery in many sedimentary basins throughout the world. In particular, Mongolia has developed several deposits for potential ISL recovery in the future (see Section 7.1). Interest has been shown in several other countries, including Tanzania, but without firm plans at the time of writing.

7. OUTLOOK

ISL uranium production has been established as an important segment of the nuclear industry. Indeed, it is expected to account for almost 50% of world production during the next few years. In the longer term, however, it seems that this percentage may decrease as more high grade deposits in Canada and additional lowgrade heap leach deposits in Africa could be brought into production. Still, ISL will continue to be a very significant component of world uranium production for the foreseeable future.

7.1. THE FUTURE OF ISL

There can be little doubt that ISL production has the ability to move to deeper and lower grade deposits as more economical deposits are depleted. It is expected, however, that competition with other forms of production such as by-product and low grade heap leach will be intense. Much will depend upon the ability of ISL to increase economic competitiveness through technological advances and to advertise its environmentally friendly properties, where this applies.

7.2. KEY FACTORS

Uranium production is strongly influenced by political and social forces as well as regulatory regimes. These influences are examined in the following sections.

7.2.1. Political and social

Political and social aspects will continue to strongly influence the development and health of the uranium mining industry, including ISL. While this much is agreed across a broad spectrum of stakeholders, and in general it is considered that this will become generally more important, the way forward is not easy to predict and such a prediction will not be attempted here.

The IAEA gives guidance on appropriate community and stakeholder consultation, and in some cases participation in decision making, in Ref. [159]. While there is some expectation that the models developing in countries such as Australia, Canada, France, Germany and the USA will become the norm worldwide, this is not certain. The widespread influence of multinational mining companies is a factor. Public expectations in the 'home' or customer countries, or corporate policy, may be to apply the strictest of home country, international and local requirements with respect to governance, social and environmental aspirations and performance.

What is considered and accepted as appropriate can be expected to develop in each country or region, informed by what happens elsewhere as a result of government, industry and non-governmental organization input.

From time to time, high level political decisions may encourage, discourage or ban uranium mining in general or uranium ISL mining in particular. Such decisions may be reversed at any time, and can be influenced by reported or real performance within the industry or the broader nuclear power industry, including nuclear weapons proliferation and nuclear accident concerns.

The accident at the Fukushima Daiichi nuclear power plant in 2011 has had a significant negative effect on public, political and non-governmental organization perspectives of nuclear power, in general, and its associated activity of uranium production. In order to mitigate such negative perspectives, the nuclear and uranium industries need to achieve near perfection in all aspects of operation.

7.2.2. Regulatory regimes

In many countries with current ISL projects and with long established regulatory regimes, regulatory requirements are sophisticated and extensive. In fact, they can potentially become cumbersome with duplication of licensing and conditions between different jurisdictions (e.g. federal and state governments in Australia and the USA) or between government departments (e.g. health/radiation, mining and environmental protection authorities). In some countries, regulatory requirements are poorly established and fragmentary. Some countries also have more general requirements regarding conventional mining of non-radioactive ores and radiation protection measures intended for the medical field, nuclear power or non-mining industrial use (e.g. density gauges, X ray machines).

Some countries may move to establish specific ISL requirements or guidelines as Australia has [154]; however, other jurisdictions may continue to apply more general guidelines or regulations. Countries that are new to ISL mining can be expected to develop their regulations further, and may or may not choose to provide ISL specific documentation.

Some joint government industry efforts have attempted to streamline regulatory requirements while keeping high levels of environmental and health protection. Australia, for example, has considered normalizing uranium mining (i.e. uranium mining is considered under the same laws and regulations as other mines, albeit with appropriate radiation protection aspects) [160]. However, this recommendation was not accepted by the government of the day [161]. Similar ongoing debates occur in the USA [133] and the same may occur in other jurisdictions in the future.

7.3. ECONOMICS AND MARKETS

7.3.1. Economics

Provided that a uranium deposit is amenable to ISL mining, this means of production is almost invariably the most cost effective. Capital costs are relatively low since mine development requires no excavation and there is no need for a crushing and grinding circuit in the processing plant. Operating costs are relatively low since productivity of the labour force can be significantly enhanced by instrumentation of both wellfields and processing plants. The overall productivity (kg U/person-hour) of ISL uranium production is very high in comparison with conventional methods. For example, US uranium mine productivity during the principal period of conventional mining (1967–1982) was 0.6 kg U/person-hour. During the period 2003–2008 when ISL dominated, productivity amounted to 1.3 kg U/person-hour. Uranium industry employment and production data for the period 1967–1982 were published annually in Statistical Data of the Uranium Industry by the US Atomic Energy Commission [162]. For 2003, this information was published in the Domestic Uranium Production Report [163] by the Energy Information Administration of the US Department of Energy. Calculations from these two data sets give the respective productivities by dividing total production for the period by total person-hours expended.

The method is not, however, without economic risk. Uranium recovery from the formation subjected to mining is difficult to predict, particularly if deposit characteristics exhibit variations in permeability, geochemistry or lithology. This risk can be offset, to a degree, by pilot plant testing (field leach trial). Groundwater restoration, where required, is also difficult to predict. Even surface reclamation may be contentious as has been demonstrated in Texas at the Hobson facility where the Bureau of Radiation Control ultimately allowed a process of soil homogenization to remediate radioactive contamination from surface irrigation with groundwater bleed [164]. Elsewhere, auxiliary elements may be elevated in ISL wastewater and become problematic (e.g. selenium [165]).

Major economic factors for ISL include ore grade, orebody thickness and lateral extension, depth, hydraulic conductivity and, finally, solution grade versus flow rate. One of the best measures of potential economic viability is the multiplication product of grade thickness as metre-percent uranium, or the productivity factor, expressed in kg U/m^2. This is a measure of the quantity of uranium that might be accessed by a particular well installation. Obviously, the more uranium accessible to a given well, the more favourable the economics. Shallow deposits require less drilling for well installation. On the other hand, deeper deposits offer higher leaching pressures and, perhaps, temperatures, both of which may enhance the kinetics of leaching. Recovery well flow rates coupled with solution grade determine the quantity of uranium entering the processing facility per unit of time. In this regard, it is important to note that economies of scale and output are particularly important in commercial or industrial scale uranium production. This situation derives from increased regulatory, administrative and legal burdens on uranium production in comparison with other mineral production. These increased burdens dictate that small projects, producing less than 400 t U/a, may prove to be less profitable or even uneconomical. This threshold is not a firm figure and may vary between localities, jurisdictions and with time.

The balance between current production output and uranium recovery is an important economic factor. ISL wells typically exhibit a progressive decline in solution grade and a progressive gain in uranium recovery. Low solution grade as processing plant feed results in low output. Just when to cease operating a particular recovery well or wellfield can be a difficult question since recovery from the uranium bearing formation impacts amortization of capital. This issue can be particularly contentious if recovery is mandated by regulatory authorities. Figure 4 provides a generic, calculated example of instantaneous (solution grade) and cumulative recovery for a single, continuously operated wellfield using the method described in Ref. [166]. Note that the leachability parameter, λ, is dependent on both orebody mineralogy and geochemistry and leaching chemistry. The maximum solution grade depends on many parameters, in particular ore grade, leachability, wellfield geometry and flow rate.

Obviously, the applicable cut-off grade in the mining solution as a condition for ceasing recovery from individual ISL patterns or wellfields is also controlled by economic factors.

ISL provides a more flexible system of extraction than most other forms of mining. This flexibility allows the operator to focus on more productive and economic areas of the deposit when prices are low and on less attractive areas when prices are high. As a consequence, many ISL operations may be better able to withstand future market volatility than conventional operations.

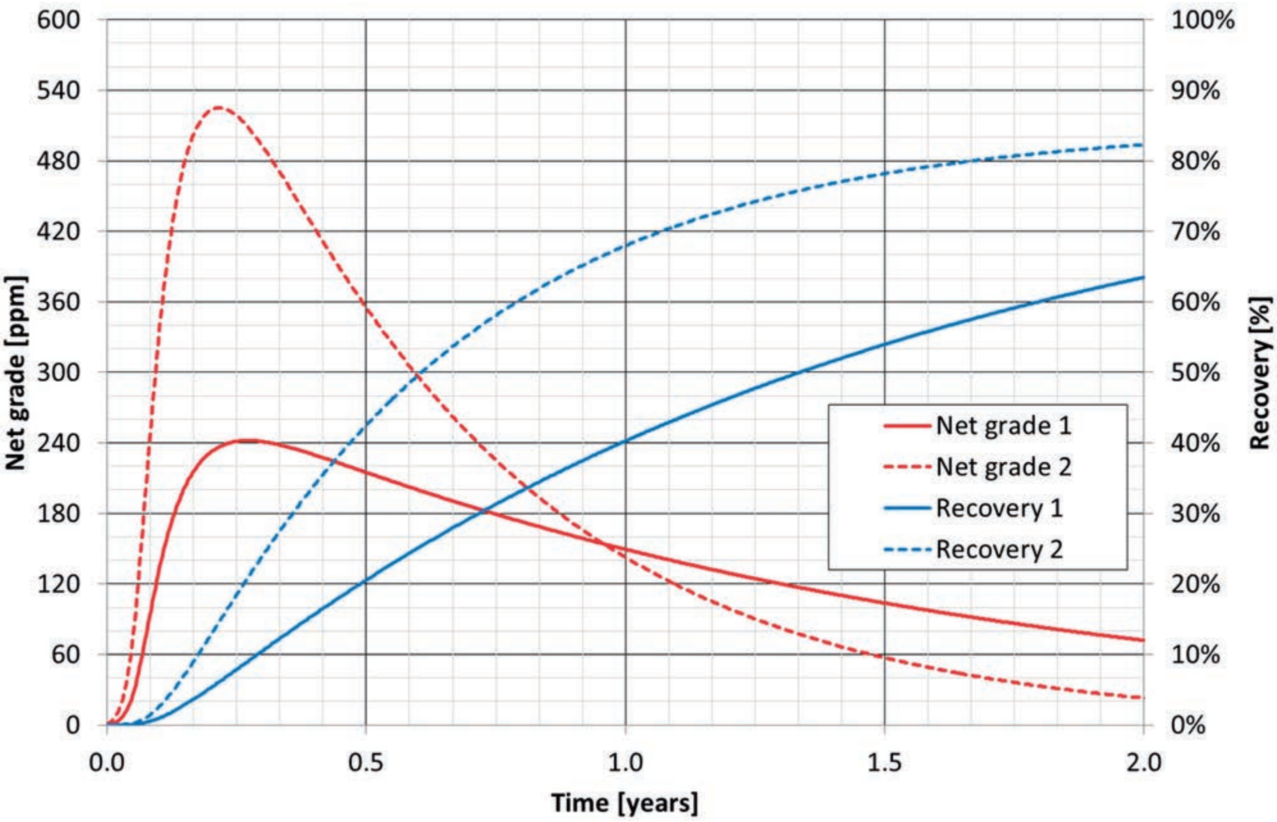

FIG. 4. Differential net recovery (as solution grade in ppm uranium) and cumulative recovery [%] simulated for typical ISL operations by considering two different leachability parameters for λ (first order kinetics): scenario 1 (solid lines), where λ = 0.002 d−1 and scenario 2 (dashed lines), where λ = 0.005 d−1 [166].

7.3.2. Markets

Overall, the demand for uranium fuel is expected to continue to be steady, or rise, for the foreseeable future. Thus, a relatively strong future market is expected to exist. This market, however, is seen to be potentially volatile owing to both politics and economics. Of potential interest is the idea promulgated in some circles that preference be given to uranium from ISL projects because of a real or perceived lesser environmental impact that conventional mining. Whether ISL uranium ever receives an environmentally friendly premium in practice remains to be seen. An independent life cycle assessment of ISL was undertaken in 2011 that might contribute to this debate [167].

7.4. TECHNOLOGY

The basic technology of acid and alkaline ISL mining has not changed greatly since its first decade, when various mining solution additives were trialled, including nitric acid and ammonium compounds, before the industry settled on sulphuric acid and carbonate/bicarbonate based leach systems [18, 168, 169]. There has been continual improvement of control systems, from manual to increasingly computerized systems, drilling techniques, instrumentation and development of ion exchange resins that are effective in high chloride mining solutions [170].

Improvements and variations of numerical models can be expected to better describe subsurface flow, extraction (dissolution) rates, possible migration of mining solution beyond mining areas (commonly called excursions) and to model groundwater remediation and post-mining groundwater quality evolution. Examples can be found in Refs [166, 171, 172].

Further developments in mining solution additives to reduce costs, environmental impact or speed groundwater remediation, where active intervention is required, will be considered [173–176]. All will require field demonstration before they would be seriously considered by producers or accepted by regulators.

Remarkable advancements and development trends in the field of ISL technology include:

- A database for wellfield planning: Advanced exploration methods and wireline borehole logging technologies can be used to map not only grade thickness (or, alternatively, productivity in kg U/m^2) contours in the mineralized horizons, but also important parameters such as permeability, redox conditions and abundance of interfering minerals. This provides a more solid basis for wellfield planning.
- Hydrological software tools for wellfield planning and operational control: The design of wellfield patterns can be remarkably improved by the use of software tools that enable the simulation of flow patterns throughout the lifetime of the wellfield. Most importantly, wellfield design can be optimized by realizing the efficient contact of the mining solution with the uranium ore in the mineralized zone (minimizing flow to barren sediments accordingly). This software enables the planning of wellfield modifications (pumping regime in general, role reversals between injectors and extractors in particular) in the course of operation for the purpose of optimization. In addition, such tools can be used to predict the risk of excursions of mining fluid and to deduce effective counter measures to cope with excursions, if observed.
- Injector/extractor well engineering: Well designs have been developed that enable rescreening (applying filter sections in two or more ore horizons) and role reversals within one and the same well.
- Geochemical software tools for ISL optimization: Whereas empirical tools are widely used for characterizing and predicting ISL performance and recovery from individual wellfield patterns of whole wellfields, a more sophisticated optimization of ISL requires the use of real chemical (reactive transport) models with properly considered kinetics of main reactions (uranium mineral dissolution and interfering reactions). There is a high potential to optimize leaching chemistry on this basis.
- Optimization of uranium recovery/processing: For the recovery of uranium from the mining solution, adsorptive effects, either in the form of ion exchange resins or solvents in solvent extraction applications, are used. The loading conditions in both ion exchange and solvent extraction plants depend on the chemistry of the mining solution. Several attempts have been made to maximize the load for better processing efficiency on the basis of both test work and process simulation software. Whereas the former provides practical data for optimization, the latter is applicable in a much wider range and enables the optimization of column operation in a more systematic manner by considering more processing scenarios more efficiently (e.g. reactive transport simulations of ion exchange sorption and elution in specific processing regimes).

7.5. ENVIRONMENTAL MANAGEMENT

Environmental management will remain an important aspect of ISL uranium mining, both because of the perceived and real impacts to groundwater and the generally heightened public and governmental attention given to uranium mines in general. In Australia and the USA, environmental aspects have been considered from the earliest days of mining [177–179], as have the issues highlighted by the IAEA in 1997 [180] and 2005 [181]. Environmental aspects are now considered in all current and former ISL mining areas (examples can be found in Refs [26–28, 30, 73, 139, 182]). Historical problems associated with ISL mining have been highlighted in the academic and public arenas (for examples, please see Refs [183, 184]) and this scrutiny has not diminished (see Refs [185, 186]). Guidance for environmental management of uranium mines in general is given by the IAEA [159], and some countries have developed specific guidelines for ISL mining with an emphasis on environmental management (e.g. Australia [154]).

The IAEA gives guidance on a risk assessment approach to environmental management in Ref. [159]. By identifying, understanding, managing and minimizing potential adverse impacts, good environmental management contributes to:

- Improved environmental outcomes;
- Demonstrated good corporate governance and accountability;
- Improved socioeconomic outcomes;
- Improved liability management;
- Reduced closure and rehabilitation costs.

Importantly, the application of best practice principles for a project begins at the conceptual phase and continues through all of the stages of the project, through operations to closure and suitability for sequential land use.

A risk based approach aims to use resources and target environmental protection and monitoring to those aspects of an operation that have the most potential to cause harm. This requires the identification of:

- A potential impact event, such as a pipeline leak of mining solution to the environment.
- Inherent risk level (e.g. low, moderate) using a matrix approach that takes into account severity and likelihood.
- Design and operational control measures, such as reduced number of joints, leakage detection and retaining structures, frequent inspections and maintenance.
- Residual risk level after design and control measures have been implemented.
- Outcome to be achieved, such as no adverse effects on biota, agriculture or drinking water at set locations.
- Outcome measurement criteria. For example, pH at set locations is not to fall below pH4 or above pH10 owing to mining caused events; water quality is to remain within agricultural quality guidelines; and ecotoxicity tests are to remain within natural variability.
- Leading indicator criteria, or early warning measurement, such as trends in pH or other water quality measures, number of minor leaks, results of periodic inspections and audits.

The influence of public or regulator concern also needs to be taken into account, within reason. This may mean monitoring of some environmental or health parameters of particular concern as a demonstration of lack of impact or attainment of regulatory concentrations, even if, from a strictly technical perspective, the risk is negligible. However, this should not be at the exclusion of management and monitoring of more realistic risks. Concerns in areas not currently highlighted by the public or regulators can rapidly become high profile if problems occur and may be discovered when it is hard to take corrective action, or require corrective action that is expensive and disruptive to people, the environment and the mining operation. Hence, a thorough, sound, scientific and engineering based risk assessment is required, and some precautions, or monitoring above those mandated by regulatory authorities, may be advisable.

Historically, one of the significant detriments to public opinion on mining, in general, and uranium mining in particular has been the failure of some operations to accumulate sufficient financial resources to remediate the project site upon completion or suspension of mining operations. Thus, many sites have had to draw upon public (taxpayer) funding in order to achieve proper remediation or restoration. This situation can be avoided through the establishment of a properly administered and secure reclamation trust fund with continuing contributions from the mining company as mining progresses, and proper assessment of the financial viability of operations before and during operations.

In summary, safety, societal aspects, environmental and radiation protection, and successful progressive and final rehabilitation will continue to be vital to ongoing uranium mining globally, for ISL mining as well as conventional mining.

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GLOSSARY

The following definitions may not necessarily conform to those adopted elsewhere for international use. Some terms may not appear in the text of this report, but they are included here because of their use in the uranium mining industry and in various listed references.

ALARA. As low as reasonably achievable (taking into account economic and social factors), a risk approach originating from radiation protection and sometimes applied to other fields.

aquifer. A permeable underground sediment or rock formation capable of storing and allowing the flow of water (groundwater).

aquitard. A low permeability underground sediment or rock formation that retards, but may not entirely prevent, the flow of water (groundwater).

baseline. Data acquired to identify the state of the environment prior to any disturbance from mining. It gives a pre-mining inventory of factors such as the diversity and abundance of flora and fauna, agricultural or pastoral activities and productivities, and quality of soil, air and water, particularly groundwater. The values acquired can be used as a benchmark for final mine rehabilitation. Social baseline data are also relevant to most projects.

bleed. In most, but not necessarily all, ISL operations, bleed is a slight excess of extracted water compared to injected water, which may vary from <1% to a few per cent of the water extracted. This helps maintain mining solutions within the planned mined areas, but also generates excess water that needs to be used or disposed of.

block leaching. The leaching of a block of ore accessed by a conventional underground mine, where mining solution is passed through a block of blasted ore and recovered.

elution. An ion exchange process. Recovery of uranium in the form of anionic uranyl complexes from loaded resin beads by a highly ionic eluent stream (containing nitrate, chloride or others), which forms a pregnant eluate with a high uranium concentration for further processing. To be followed by a resin regeneration (also referred to as conversion) for reuse in the sorption circuit (compare with sorption).

environmental impact assessment or statement. An assessment or statement of the environmental impacts of a project, usually incorporating some form of risk assessment and measures proposed to minimize identified expected or possible negative impacts. May include a social impact assessment.

excursion. Movement of mining or waste solution beyond the area intended. There may be specific definitions of what constitutes an excursion, how it needs to be reported, and the timing of corrective actions if the latter is required.

extraction well (or bore). A cased well with a filter section through which mining solution is removed by pumping from the orebody being mined.

hydraulic conductivity (permeability). The inherent ability of porous rock to transmit fluid (compare with transmissivity).

injection well (or bore). A cased well with a filter section through which mining solution is introduced to the orebody being mined either by being pumped or by gravity flow. The mining solution is removed via an extraction (or recovery) well.

in situ leach(ing) or in situ recovery. A form of solution mining where mining solution is circulated underground through a sedimentary, hydraulically saturated orebody to dissolve and bring the target material to the surface for further recovery.

ion exchange. Transfer (absorption/desorption) of ions between a solution and ion exchange sites on surfaces (on and inside porous ion exchange resin beads in uranium recovery applications). Predominant technology to recover uranium from loaded mining solutions in ISL applications (compare with sorption and elution).

mining solution. Usually local groundwater that is chemically modified to cause it to dissolve the target mineral (uranium) when it is caused to move through an orebody by pumping. Mining solutions for uranium ISL are either alkaline (usually carbonatic) or acidic (usually sulphuric), generally with the further addition of an oxidizing agent such as gaseous oxygen or hydrogen peroxide. Typically sulphate or carbonate act as a complexing agent in the uranium dissolution process.

non-governmental organization. A non-profit body independent of the State and of any government agency, such as a trade union, progress association, industry organization, social or environmental organization. These may be formal, informal, local, national or international.

observation well (or bore), also called monitoring well (or bore). A well installed in, above, below or laterally to the orebody being mined to allow water level measurement and/or groundwater sampling. This allows the hydrogeology to be understood and to specifically identify possible movement of mining solution beyond the mining area, or to identify potential impacts on identified users or receivers of groundwater in the vicinity of an operation.

ore. An occurrence of a mineral in quantity and quality that could be mined economically. Note that there may be official, more detailed definitions in some jurisdictions.

palaeochannel. Remnant of an inactive river/stream that has been filled or buried by younger alluvial-fluvial sediments. Potential host formation of secondary uranium deposits in the form of elongated lenses, sometimes forming roll fronts as well. May be called a basal channel if the fluvial sediments are incised into the underlying geological formation.

pattern (well pattern). Refers to the design of the locations of injection and extraction wells relative to one other. A pattern may refer to a single extraction well and an injection well that serves it.

public environment report. Typically a smaller form of an Environmental Impact Statement, or a report of environmental performance of a project released publically.

roll front deposit. A mineral deposit formed within porous rocks in vertically confined aquifers, typically sandstone, when naturally mineralized groundwater containing uranium is subjected to changes in oxidation redox potential and pH conditions causing precipitation of uranium, forming crescent shaped deposits (in cross-section) that are convex down gradient.

solvent extraction. Separation process in which a water based mining fluid and an organic based solvent are brought into contact to selectively extract a component, in this case uranium, from the mining fluid.

sorption ion exchange process. Adsorption of uranium (in form of anionic uranyl complexes) from the loaded mining solution to resin beads in an ion exchange column as part of the recovery process (compare with elution).

tabular deposit. Subhorizontal, usually thin and laterally extensive ore bodies within reduced fluvial sandstone, created by the distribution of uranium in parallel with sedimentary bedding.

transmissivity. The ability of porous rock to transmit fluid, generally applied to a layer of rock of a certain thickness (compare with hydraulic conductivity/permeability).

wellfield. An area of mining wells and associated observation wells that forms a mining unit. Typically the area is contiguous but more than one separated orebody within pumping distance may be included.

CONVERSION FACTORS

Different definitions of units and specific characteristics of ISL operation have been used in the past and are still used at present, in particular units other than SI units (e.g. US units) and different definitions of characteristics are used in various regions of the world.

Table 1 summarizes the most important physical quantities relevant to ISL deposits and operations.

TABLE 1. PHYSICAL QUANTITIES RELEVANT TO ISL DEPOSITS AND OPERATIONS

Physical quantity	Reference unit/definition	Alternative unit/ definition	Conversion
Concentration	mg/L	ppm	1 mg/L = 1 ppm
	µg/L	ppb	1 µg/L = 1 ppb
Conductivity (hydraulic)	m^2	d (darcy)	1 m^2 = 1.013 250 3 $\times 10^{12}$ d
			1 d = 9.869 23 $\times 10^{-13}$ m^2
	Special case — water at 1cP (centipoise) = 1 mPa·s viscosity and 1 g/cm^3 specific gravity (about 20 °C):		
	m/s	d (darcy)	1 m/d = 1.202 35 d
	(= 86 400 m/d)		1 d = 0.831 71 m/d
		ft/d	1 m/d = 3.280 84 ft/d
			1 ft/d = 0.304 80 m/d
		gpd/ft^2	1 m/d = 24.542 gpd/ft^2
		(= gal/d/ft^2)	1 gpd/ft^2 = 0.040 746 5 m/d
		(= 1 Meinzer)	
Flow rate	L/s	gal/min (US)	1 m^3/h = (1/3.6) L/s
	m^3/h		1 L/s = 15.850 32 gal/min
			1 gal/min = 0.063 090 2 L/s
			1 m^3/h = 4.402 868 gal/min
			1 gal/min = 0.227 124 7 m^3/h
GT (grade·thickness)	GT	Productivity P [kgU/m^2]	$GT = (100\%/\rho_{ore}) \cdot P$
			(ρ_{ore} – specific gravity of ore)
	GT[wt%U·m]		GT[wt%U·m] ≈ 0.058·P[kgU/m^2]
			GT[wt%U_3O_8·m] ≈ 0.068·P[kgU/m^2]
	GT[wt%U_3O_8·m]		
Length	m (metre)	ft (foot)	1 m = 3.280 84 ft
			1 ft = 0.304 8 m
Mass	kg	lb	1 kg = 2.204 623 lbs
			1 lb = 0.453 592 4 kg
Permeability (hydraulic)	See: Conductivity (hydraulic)		
Pressure	kPa	psi	1 kPa = 0.145 037 7 psi
			1 psi = 6.894 757 kPa
Radioactivity	Bq	Ci	1 Bq = 2.7 $\times 10^{-11}$ Ci = 27 pCi
			1 Ci = 3.7 $\times 10^{10}$ Bq = 37 GBq

TABLE 1. PHYSICAL QUANTITIES RELEVANT TO ISL DEPOSITS AND OPERATIONS (cont.)

Physical quantity	Reference unit/definition	Alternative unit/ definition	Conversion
Temperature	°C	°F	°C = (°F - 32)·5/9 °F = (°C·9/5) + 32
Transmissivity (hydraulic)	m^2/s (= 86 400 m^2/d)	ft^2/d	1 m^2/s = 9.300 0 × 10^5 ft^2/d 1 ft^2/d = 1.075 27 × 10^{-6} m^2/s 1 m^2/d = 10.764 ft^2/d 1 ft^2/d = 0.092 902 m^2/d
		gpd/ft	1 m^2/s = 6.956 9 × 10^6 gpd/ft 1 gpd/ft = 1.437 42 × 10^{-7} m^2/s
Uranium mass equivalent	U equivalent	U_3O_8 equivalent	m(U) = 0.848 004 71 m(U_3O_8) m(U_3O_8) = 1.179 238 73 m(U)
	kg U	lb U_3O_8	1 kg U = 2.599 776 83 lb U_3O_8
Uranium tonnage	t U (= 1000 kg U)	t U_3O_8 (metric tonne) ST U_3O_8 (ST – short ton)	1 t U = 0.848 004 71 t U_3O_8 1 t U_3O_8 = 1.179 238 73 t U 1 ST = 2000 lbs 1 ST U_3O_8 = 907.184 8 kg U_3O_8 1 ST U_3O_8 = 769.297 kg U
Volume	m^3 (= 1000 L)	gal (US)	1 m^3 = 264.172 1 gal 1 gal = 0.003 785 412 m^3

LIST OF ABBREVIATIONS

The following abbreviations may not necessarily conform to those adopted elsewhere for international use. Some terms may not appear in the text of this report, but they are included here because of their use in the uranium mining industry and in various listed references.

ALARA	as low as reasonably achievable (a risk approach)
BPT	best practice/practicable technology
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
d	darcy (old unit of hydraulic conductivity/permeability)
EIA(EIS)	environmental impact assessment (statement)
ENA	enhanced natural attenuation
EPA	Environmental Protection Agency
EPBC	Environmental Protection and Biodiversity Conservation, Australia
eU_3O_8	uranium measured by γ-logging
FLT	field leach trial
GEIS	general environmental impact statement
GT	grade-thickness (wt% × m)
HP	horse power
ISL	in situ leach(ing)
ISR	in situ recovery
IX	ion exchange
JORC	Joint Ore Reserves Committee, Australia
MARP	Mining and Rehabilitation Program
MNA	monitored natural attenuation
NA	natural attenuation
NGO	non-governmental organization
NRC	Nuclear Regulatory Commission, USA
PAA	product area authorization
PER	public environmental report
RAR	reasonably assured resources
RML	radioactive materials licence
ROPO	recognized overseas professional organization
SEC	Securities and Exchange Commission, USA
SME	Society of Mining, Metallurgy and Exploration, USA
ST	short ton
SX	solvent extraction
TDS	total dissolved solids
TRV	target restoration value
UIC	underground injection control
UNFC	United Nations Framework Classification
UOC	uranium ore concentrate
USDW	underground sources of drinking water
U_3O_8	uranium oxide (reference form of uranium oxide for trading)
wt%	weight per cent

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Technical Meetings

Vienna, Austria: 7–9 June 2010; 15–18 April 2013

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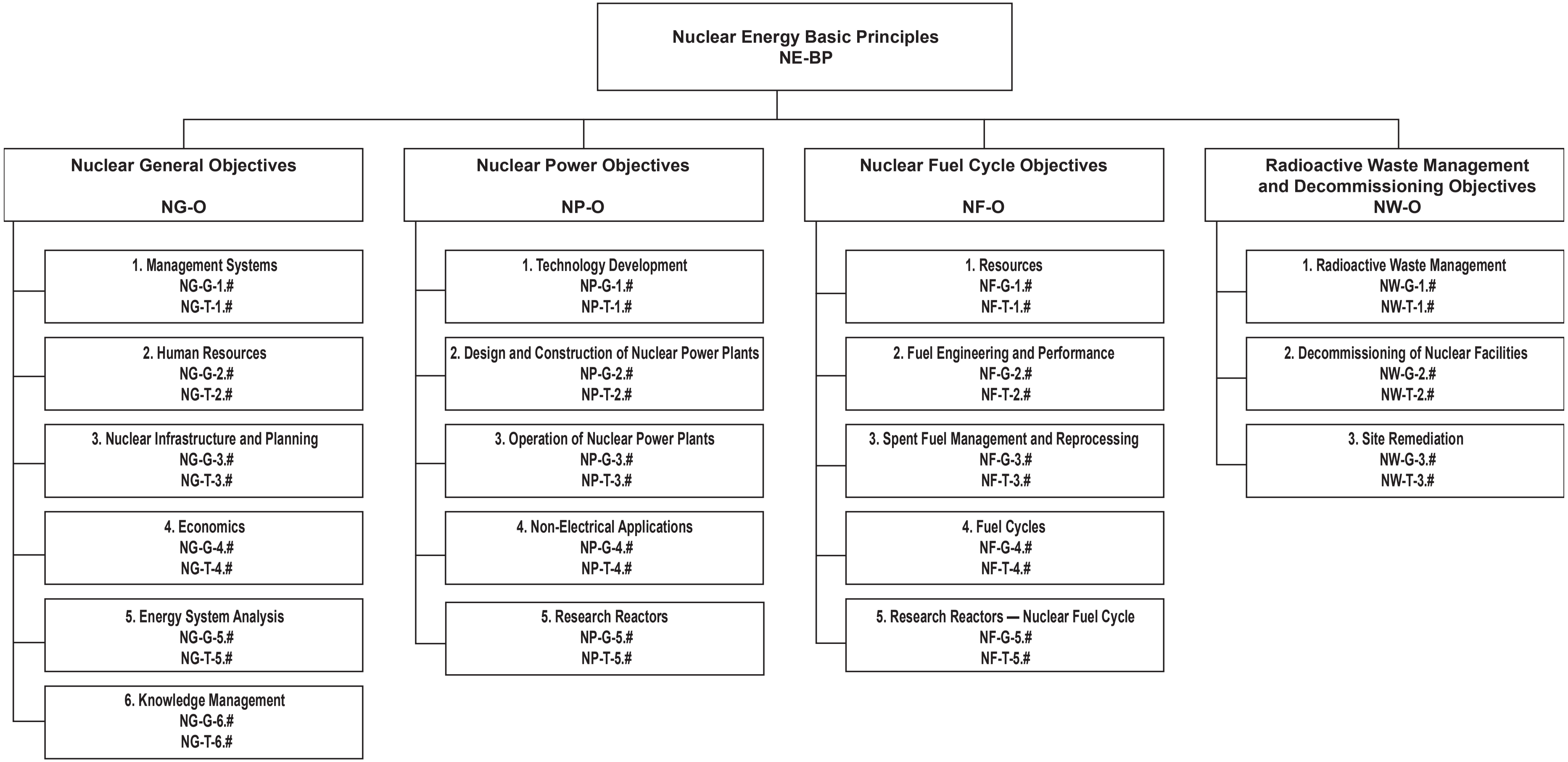

Key

BP: Basic Principles
O: Objectives
G: Guides
T: Technical Reports
Nos 1-6: Topic designations
#: Guide or Report number (1, 2, 3, 4, etc.)

Examples

NG-G-3.1: Nuclear General (**NG**), Guide, Nuclear Infrastructure and Planning (topic **3**), **#1**
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NF-T-3.6: Nuclear Fuel (**NF**), Report (**T**), Spent Fuel Management and Reprocessing (topic **3**), **#6**
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