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IAEA'S OVERVIEW OF WORLDWIDE IN SITU LEACH URANIUM MINING

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ABSTRACT

In situ leach or leaching (ISL), also called in situ recovery (ISR) uranium mining, has become one of the standard production methods for this energy metal. ISL's application to amenable uranium deposits, in certain sedimentary formations, has grown over the last two decades in consequence of its competitive production costs and low surface impacts. A recent IAEA publication (In Situ Leach Uranium Mining: An Overview of Operations, IAEA Nuclear Energy Series No. NF-T-1.4 (2016)), provides an historical overview and shows how ISL experience around the world can be used to direct the development of technical activities, taking into account environmental considerations and emphasizing the economics of the process, from exploration, development and operations to responsible mine closure. The publication provides information on how to design, operate and regulate current and future projects safely and efficiently, with a view to maximizing performance and minimizing negative environmental impact.

Keywords: In Situ Leach, In Situ Leaching, In Situ Recovery, Uranium Mining, IAEA.

INTRODUCTION

In situ leach (ISL), also called in situ leaching or in situ recovery (ISR) mining, has become one of the standard uranium production methods, following early experimentation and production in the 1960s. Its application to amenable uranium deposits (in certain sedimentary formations) has been growing in consequence of its competitive production costs and low surface impacts. In 1997, the ISL share in total uranium production was 13%; by 2009 it had grown to over 30%, reaching 46% in 2011 and 51% in 2014. In the past, ISL technology was applied mainly in Bulgaria, the Czech Republic/Czechoslovakia, Kazakhstan, Ukraine, the United States of America and Uzbekistan. Recently, it has been used in Australia, China, Kazakhstan, the Russian Federation, the USA and Uzbekistan, with minor operations or experiments conducted elsewhere.

The IAEA released an overview publication in 2016 to illustrate how ISL experience gained around the world can be used to direct the development of technical activities, taking into account environmental considerations and with an emphasis on the economics of the process, including responsible mine closure(1). With this publication, the IAEA's Member States and interested parties have more information with which to take informed decisions regarding the design and the efficient and safe regulation of current and future projects, with a view to maximizing economic performance and minimizing negative environmental impact. Highlights of the publication's findings are provided in this paper along with a summary of the IAEA's involvement in ISL over recent decades. Text has been abbreviated from the report(1) and includes some updates. Many reference links are provided in the full report, but of necessity only a selection are included in this paper, together with some other significant recent publications on the subject.

FUNDAMENTALS

Brief Definition

The uranium ISL method is defined in the IAEA report(1) as the extraction of uranium from the host (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: (i) injecting a suitable leach solution into the ore zone below the water table, (ii) oxidizing, complexing, and mobilizing the uranium, (iii) recovering the pregnant (loaded) solutions through production wells (extraction wells or recovery wells) and (iv) pumping the uranium-bearing solution to the surface for further processing. Several useful general descriptions are available in the literature (2-6).

Conditions of Application

The IAEA report(1) considers that the

"following major conditions are necessary in order to apply the ISL method of mining uranium[1]:

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

> "ISL for uranium recovery is usually applied to ores confined to water-saturated sandstone aquifers of variable consolidation… 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

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

> permeability limit… ISL mining involves the extensive recycling of lixiviant as only a limited proportion of the uranium is mobilized with each 'pass' of 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 to 100 times or sometimes more to achieve the targeted recovery, over a period ranging from a few months to two or more years.
>
> "An orebody normally occupies only part of its hosting aquifer, which by its nature is typically in semi-confined 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 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."

Importance of Environmental Aspects

Good design and construction of extraction and injection wells is required to avoid the contamination of non-target aquifers with mining or disposal liquids, as well as to minimize the risk of surface spills or environmental hazards caused by other infrastructure, including the processing plant and any associated ponds. Good environmental practices are described in documents such as the U.S. Nuclear Regulatory Commission's Generic Environmental Impact Assessment for In-situ Leach Uranium Milling(7) and the Australian Federal Government's In situ Recovery Uranium Mining Best Practice Guide(8), as well as a number of older IAEA reports referred to in the recent IAEA report(1).

Radiation Protection

Although uranium ore is not exposed at the surface, nor are radioactive tailings produced, the management of radiation risk remains important at ISL uranium mines, albeit that the risks are in general lower than those at a conventional uranium mine with a similar production capacity. Precautions are particularly important at the final purification and packing stages of the uranium ore concentrate product. The need for a radiation management plan and radioactive waste management plan, with their appropriate and demonstrable implementation, is asserted here, but no specific discussion or advice is within the remit of the IAEA report(1) or this paper. Guidance for these aspects must be found elsewhere.

Recovery Technologies: Leaching

Internationally, sulfuric acid is the dominant leaching medium (Australia, Kazakhstan and Uzbekistan), whereas currently in the USA only alkaline leaching is used. Just as important is the highly oxidizing nature of the lixiviants, which is maintained by the addition of oxidizing agents ranging from, but not restricted to, air or oxygen through to hydrogen peroxide and ferric iron.

The IAEA report(1) summaries the main criteria used in choosing between acid or alkaline leaching reagents as follows:

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

Typically, it is the abundance of carbonate in the ore that drives the decision. One frequently quoted 'rule of thumb' is that for the economic leaching of uranium ore using the acid route, the carbonate content of the ore should be less than 2%, otherwise the alkaline leaching route is preferred. However, like all rules of thumb, this figure should be treated with caution and used as an initial guide only, as other factors may drive a decision regarding the most appropriate method.

Recovery Technologies: Extraction

On the basis of broad industry experience, as summarized by the IAEA report(1), there are "two main pathways for the further recovery and processing of uranium extracted in mining solution; ion exchange (IX) and solvent extraction (SX), or potentially a combination of the two." Historically and currently, ion exchange is the dominant method for both acid and alkaline leaching. Solvent extraction has sometimes been preferred for ISL amendable uranium deposits where the salinity, and particularly the chlorinity, of the groundwater present (and therefore the lixiviant, which is fortified groundwater) is high. Over the last two to three decades, IX resins have been developed to be effective up to about 5 mg/L or reportedly higher(9,10). The best known recent ISL uranium projects to use SX are Honeymoon in Australia(11,12) and Uzbekistan operations(1); others use IX.

Satellite Mining

This term refers to uranium extraction at a location away from a main processing plant. In the case of ISL, uranium is extracted and partially processed at a satellite mine, typically to the stage of uranium loaded resin. The resin is then trucked to a main processing plant for further treatment and purification to a saleable product. It has been used in both the USA and Kazakhstan for a number of years and was introduced in Australia (Beverley North) in 2010–2011(13) and since then to the Four Mile(14) operation. Resin is regenerated at the central plant and returned to the satellite plant for reuse. In Uzbekistan, a later stage intermediate product is produced which is transported elsewhere for final processing(1).

Groundwater Remediation and Closure

According to the IAEA report(1)

"remediation[2] of residual mining (and in some cases disposal) solution that remains in the mined aquifer at the completion of mining may or may not be required, depending on the prevailing regulatory environment, the original pre-mining quality of groundwater in the aquifer intended for mining, the known or expected end-use of the aquifer, the connectedness of the mined aquifer to other groundwater resources, users or the environment, and the likelihood of migration of residual mining or disposal water."

This issue, which can be contentious, is discussed further in References (1) and (15).

In brief, groundwater remediation of uranium ISL mines under closure is being undertaken in the Czech Republic(16) on acid ISL mines and in the USA on alkaline leach ISL mines(17). Examples of projects where monitored natural attenuation is practiced or proposed include Australia and Kazakhstan.

Regardless of the closure method used, all groundwater wells not required for ongoing monitoring should be appropriately decommissioned at the end of mining — or preferably, progressively — to avoid the possibility of cross-aquifer contamination. Similarly, at the end of mining, all surface facilities not handed over for subsequent use should be appropriately decommissioned and the land surface returned to an agreed post-mining land use.

INTERNATIONAL OVERVIEW

The IAEA report(1) recalls that the ISL of uranium commenced in the 1960s in both the former Soviet Union and Eastern Block and the USA. There was modest application of the technology in both areas by the late 1970s. Development then stagnated for several decades, largely due to low uranium prices. The dissolution of the former Soviet Union in the early 1990s opened the door to western investment in central Asia, with price increases in the early 2000s spurring a rapid increase in investment and subsequent increased production.

A discussion on the ISL uranium mining experience in different countries is provided in the IAEA report, as summarized in Table 1.

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

Table 1: International Overview of Uranium ISL Mining

Country	Active years	Notes
Australia	Tests from 1977, mining 2000–present	Four deposits in South Australia have been mined. Other deposits have been investigated to various degrees
Bulgaria	Production 1967–1992	Some production during environmental cleanup since 1992
China	Tests from 1970, production since 1991	Ongoing interest and development
Czech Republic/ former Czechoslovakia	Tests from 1967, production 1971–1995	Small production during environmental cleanup since 1995
Hungary	Tests 1988	Tests showed Dinnyerberki deposit was not amenable to ISL mining
Kazakhstan	Tests from 1970, production since late 1970s–present	Since 2000, rapidly expansion saw Kazakhstan become the world's leading uranium producer in 2009, a position maintained until the present day
Mongolia	Tests since 1994	Significant potential to enter commercial production
Niger	Tests in early 2000s (hydraulic only, no leaching)	Tests showed Imouraran deposit was not amenable to ISL mining
Pakistan	Tests from 1990, intermittent production since 1995	Small scale by world standards
Russian Federation	Tests from 1984, production since mid-2000s	Production was increased slowly at the Dalur and Khiagda deposits
Tanzania[3]	Tests 2012	Deposit development on hold, method or method combination still under consideration
Ukraine	Intermittent production 1966–1993	Three deposits mined by ISL, possibilities for future ISL production
USA	1961–present	One early acid project, all others alkaline leaching
Uzbekistan	1961–present	Second highest cumulative ISL production after Kazakhstan

OUTLOOK

The Expected Future of ISL Uranium Mining

ISL uranium mining recently passed the 50% mark of world mine production and seems likely to remain the dominant mining method for uranium for the next few years at least. In the longer term, this percentage may decrease as additional underground high grade production in Canada is likely as uranium prices recover, and as additional low grade heap leach (perhaps with upgrading) deposits in Africa are potentially brought into production. Nevertheless, ISL has the ability to exploit deeper and lower grade deposits. Its relative position as a method of uranium mining compared with other means will depend on its ability to remain competitive through efficiencies and technological advances. The mining technology's low surface 'footprint' can also be an advantage in reducing environmental impact, where groundwater aspects are adequately addressed.

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[3] Not included in the IAEA report(1) (see Reference (18)).

Key Factors

Uranium production in general is strongly influenced by political and social forces as well as by the prevailing regulatory regimes. Social, political and regulatory aspects will continue to strongly influence all forms of uranium mining, with ISL being no exception. As well as environmental protection, appropriate community and stakeholder consultation is recommended by the IAEA(19) and others (see References (20) and (21)). The models developing in some 'western' countries may not necessarily translate directly into best practice in new areas of ISL uranium mining. Hence, it is important to remember that what is considered and accepted as appropriate can be expected to develop in each country or region, taking into account local circumstances and culture and *informed* by what happens elsewhere through inputs from government, industry and non-governmental organizations.

Economics

A uranium deposit that is amenable to ISL mining has meant that this mode of production is nearly always the most cost effective. Capital costs are relatively low, as no mining excavations or crushing/grinding circuits are required, and operating costs are also often relatively low. However, the method is not without economic risk. Uranium recovery from the mined formation can be difficult to predict, particularly if the characteristics of a deposit show variations in lithology, geochemistry, permeability and the like. This risk can be offset, to a degree, by a field leach trial (pilot testing)(22). The likelihood of success, or at least the time frame and cost of success of groundwater restoration, where required, can also be difficult to predict.

Despite its reputation in some circles as a method for mining low grade uranium deposits, which is indeed demonstrated at some sites, the ore grades of some deposits such as Beverley and Four Mile in Australia are over 0.1% U and comparable to many conventional mines. Economies of scale and output are important in all commercial or industrial-scale uranium production, although ISL may be more economic for smaller deposits and production rates than is conventional mining.

Technology

The basic technology of alkaline and acid ISL uranium mining has not changed greatly after the first decade or two, where various alkalis and acids were trialled until the industry settled on carbonate–bicarbonate and sulfuric acid, respectively (although there are exceptions). The improvement in control systems and automation has been marked and, as already mentioned, the development of IX resins that operate effectively at high chlorinity has also been important. Advances in drilling methods include well designs that allow rescreening. Numerical modelling has also advanced, especially with regard to geophysical data and linked groundwater flow and geochemical interactions (and hence uranium recovery rates and, where required, aquifer restoration rates). The IAEA report(1) notes:

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

Environmental Management

Good environmental management is, and will remain, an important aspect of ISL uranium mining and indeed of all mining, both because of the generally heightened attention given to uranium mines in general by the public and governments(20, 21, 23) and in particular because of the perceived and real impacts to groundwater. Historical groundwater contamination at the former ISL uranium mines in the Czech Republic are well known(16) and actual or perceived difficulties elsewhere have also been publicized. This combination of historical fact and ongoing concerns continues to influence some aspects of public opinion and the government approach to ISL uranium mining.

The IAEA(10,19) recommends a risk assessment approach to environmental management. The 2016 IAEA report(1) suggests that 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."

Further guidance is given in Section 7.5 of the report, and in many references cited throughout the report, a selection of which has been cited here.

CONCLUSIONS

ISL mining of uranium is nowadays the dominant production method employed due, primarily, to its application in Kazakhstan and Uzbekistan, together with significant contributions from Australia, China and the USA and minor contributions elsewhere. This dominance is likely to continue over the next few years at least. Although the basic technology has been established for decades, significant improvements in many areas are apparent and ongoing improvements to the technique will be required to enable it to maintain its place as a major uranium production method. This situation is likely to prevail as long as additional ISL amenable deposits continue to be discovered and their viability for mining demonstrated.

Further to these technological aspects, the IAEA report(1) concludes:

> "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, to ISL as much as more 'conventional' mining."

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