Ore Geology Reviews 79 (2016) 500–514

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

In situ recovery, an alternative to conventional methods of mining: Exploration, resource estimation, environmental issues, project evaluation and economics

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ARTICLE INFO

Article history:
Received 1 October 2015
Received in revised form 15 June 2016
Accepted 19 June 2016
Available online 21 June 2016

Keywords:
In-situ recover
In-situ leach
History
Commodities
Applicability of ISR
Environmental issues
Economics
Exploration
Assessment
Uranium
Copper
Gold
Nickel
Molybdenum
Scandium
Rhenium
Vanadium
Selenium

ABSTRACT

This paper discusses the history and application of in situ recovery (ISR) to a wide variety of metals. The increasing application of ISR may provide an important method to address a key issue for the mining industry, namely the cost of production.

ISR transfers a significant proportion of hydrometallurgical processing to mineralised bodies in the subsurface to directly obtain solutions of metals of interest. As a result, there is little surface disturbance and no tailings or waste rock are generated at ISR mines. However, for ISR to be successful, deposits need to be permeable (either naturally or artificially induced), and the metals of interest readily amenable to dissolution by leaching solutions in a reasonable period of time, with an acceptable consumption of leaching reagents.

The paper discusses the following aspects of ISR:

- *History*. ISR for uranium was introduced in 1959 in the USA, and subsequently applied in many countries over last 50 years, particularly in the USSR. The share of uranium mined by ISR reached 51% of world production in 2014, and the capacity of ISR mining of uranium is now comparable with that from conventional uranium mines.
- *Commodities*. A review of the use of ISR for mining other commodities, namely copper, gold, nickel, scandium, rhenium, rare earth elements, yttrium, selenium, molybdenum, and vanadium. ISR for copper was introduced in the 1970s and there were several successful natural tests and mines. Scandium, rhenium, rare earth elements, yttrium, selenium, molybdenum, and vanadium were mined in pilot tests as by-products of uranium extraction. ISR of gold, copper, nickel, rare earth elements and scandium has been successfully developed over recent years. The paper discusses other commodities that have potential to be mined using ISR.
- *Applicability of ISR* is addressed by a discussion of the features of mineralisation that need to be considered during different stages of ISR projects. Permeability,[1] hydrogeological conditions and selective leachability are the most critical parameters for ISR, and must be defined in the evaluation and exploration stages. Morphology and depth of mineralisation, thicknesses and grades, distribution of mineralisation, presence of aquicludes, and environmental conditions are also important factors for ISR projects.
- *Environmental issues*. ISR allows the extraction of mineralisation with minimal disturbance to existing natural conditions. In contrast to underground and open pit mining, there are smaller volumes of mining and hydrometallurgical effluents that require management. Clearly contamination of groundwater by ISR reagents is the critical aspect requiring management during an ISR operation. Control of leaching in ISR operations and various ways of cleaning aquifers are discussed in the paper.
- *Economics*. ISR operations deliver a range of benefits including lower CapEx costs for mine development, processing plant and infrastructure. ISR enables production to start at low capital cost and then a modular increase in production, as well as very flexible production capacity. The costs of ISR for different commodities (copper, gold, nickel, scandium, rhenium, rare earth elements, yttrium, selenium, molybdenum, vanadium) are discussed, with economic parameters for uranium production from ISR and conventional provided for comparison. The CapEx, OpEx and common cut-off grades for ISR for different commodities are discussed.

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[1] More accurately is hydraulic conductivity or permeability coefficient, m/day.

http://dx.doi.org/10.1016/j.oregeorev.2016.06.016

- *Exploration, resource estimation and the development of ISR projects* require a number of different approaches compared to conventional mining projects. These criteria and the necessary methodology for resource estimation for ISR projects are described in the article.

Contents

1. Introduction

Globally, the mining industry faces a number of challenges, including:

- increasingly rapid depletion of low-cost, high profit, deposits, mined by conventional methods;
- increasing costs of mining and processing;
- accumulation of tailings, requiring expensive management and ongoing monitoring;
- reduced and variable commodity prices (Bloomberg Commodity Index, 2015); and,
- consequently, reduced profitability and return on investment.

Innovation and new approaches to the extraction of minerals provide answers to these challenges.

In situ recovery (ISR) is the one of the most effective methods to address the costs of mining. The key feature of ISR is transferring a significant proportion of the hydrometallurgical processing the mineralised bodies to the subsurface to directly obtain solutions of metals of interest.

ISR technology has been in existence for 65 years, but was only widely developed for uranium production in South Kazakhstan last the last 10–15 years with strong improvements in experience in applying ISR. This technology has been used for copper for 40 years, but the first experience was not entirely positive. Copper and gold mines have operated successfully over the last 10-15 years in Russia building on the uranium ISR experience. At Dalur, a uranium mine in Russia, a plant is under construction to extract scandium and rare earths as byproducts from the uranium pregnant solutions. It is the authors' opinion that the growing experience in ISR technology will allow the technique to be adopted more widely.

The evaluation of the suitability of deposits for ISR requires different and/or modified approaches compared to traditional mining/extraction techniques. Furthermore, some deposits that are currently uneconomic to extract using traditional mining methods may be a profitable as ISR operations.

An important reason for the slow uptake of ISR technology is the lack of experience and expertise in ISR, and the need for a somewhat more complex approach for resource estimation for deposits to use ISR.

This article is aims to highlight key features of current ISR practice, based on modern technologies and in challenging economic conditions.

2. What is *in situ* recovery?

Conventional mining in open pit and underground mines involves removing ore (and waste) from the ground, and then processing it to extract the metals of interest.

In situ recovery (ISR), also known as *in situ* leaching (ISL), use solutions that are pumped through the mineralized body *in situ* (underground) to recover metals by leaching. *In situ* mining according to Bates and Jackson (1987), a definition endorsed by The National Academy of Sciences (2002), is the “removal of the valuable components of a mineral deposit without physical extraction of the rock”.

Operations at typical ISR mines comprise well field/s and an extraction process plant/s. Leaching solutions are pumped into the mineralized zone/s through a network of injection bores and extracted by production bores. In the process, the leaching solution dissolves the metals of interest, which are brought to surface in a pregnant solution (Fig. 1).

The pregnant solutions are treated at an extraction plant producing a chemical concentrate of the target metal/s.

As a result, there is little surface disturbance and no tailings or waste rock are generated at ISR mines.

However, for ISR to be effective the mineralized body needs to be permeable (either naturally or artificially) to the solutions used, and located such that the solutions do not contaminate groundwater away from the mineralized body. Target minerals need to be readily soluble in the leaching solutions for recovery in a reasonable period of time, and these should be a reasonable consumption of leaching reagents.

3. History of ISR

In situ recovery (ISR)[2] uranium mining technology was developed independently in both the USSR and in the USA in the late 1950s to early 1960s. It was developed in both countries using similar engineering and technological approaches. However, the Soviets adopted the acid leach system, while the US specialists employed an alkaline, primarily carbonate-based, system (IAEA, 2001) (Fig. 2).

The first field tests of acid ISR technology for extracting uranium took place at the Devladovo Deposit, Ukraine. But the first commercial scale ISR operations in the USSR took place at the large sandstone-

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[2] Also known as *in situ* leaching or ISL.

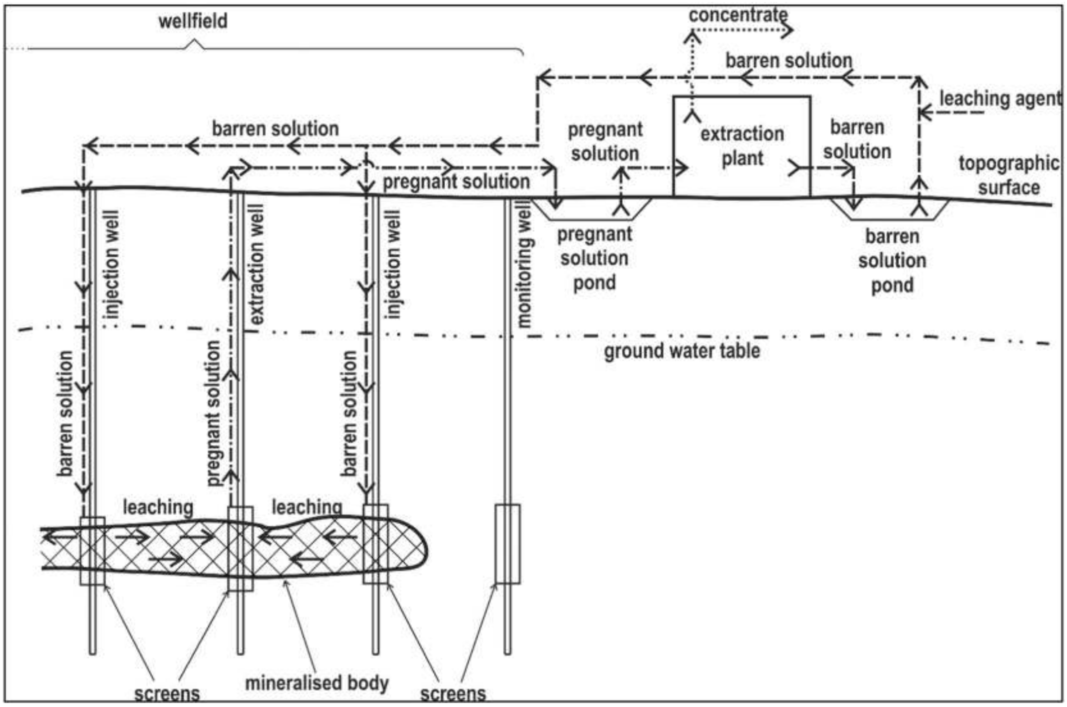


Fig. 1. Conceptual *in situ* recovery mine.

hosted Uchkuduk Uranium Deposit, now in Uzbekistan but part of the USSR at the time, where operational difficulties coincided with the experiments on ISR in Ukraine.

The mineralized bodies at Uchkuduk occur at depths ranging from 10 m to 500 m below surface. The deposit was initially operated as an open pit and then by an underground mine. However, the conditions for underground mining were unfavourable: artesian waters with temperatures 30–40 °C, unstable crumbly rocks, and low uranium grades. As a result, mining of this deposit was complicated and dangerous (Pyatov, 2005).

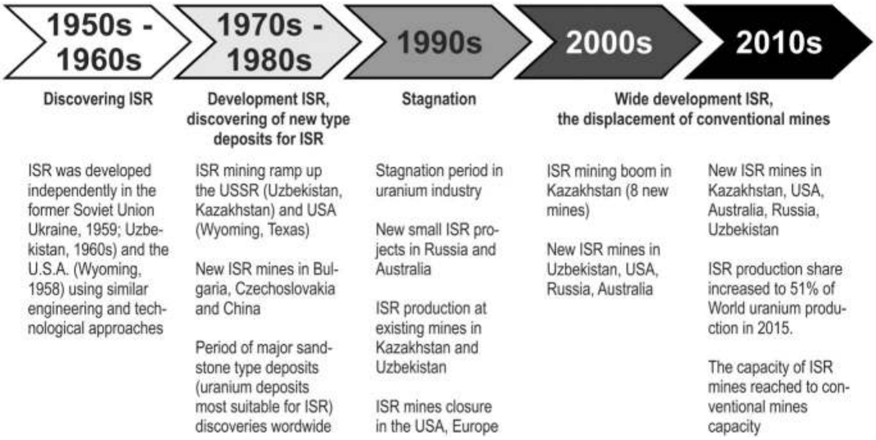
Unfavourable conditions for underground mining were however favourable for the use of ISR. The first experiments with ISR at the Uchkuduk Deposit were successfully completed in the mid-1960s, and ISR operations began delivering commercial quantities of uranium in the early 1970s (Pyatov, 2005) (Fig. 2). During the same period, ISR was developed at uranium deposits in Wyoming and South Texas in the USA (Boytsov, 2014).

Provinces with sandstone roll-front uranium deposits amenable for ISR mining were discovered in the 1970s and 1980s on almost all continents (Kazakhstan, Uzbekistan, Australia, China, Russia, USA, and other countries). These deposits are now the foundation of the uranium industry (Fig. 2).

The strongest development of ISR occurred during the 2000s and 2010s. Uranium production share by ISR in the world increased from 20% in 2005 to 51% in 2014 (WNA, 2015). Individual ISR mines now produce up to 2000 t U per year (*e.g.* Tortkuduk, South Moyinkum, Karatau and Akbastau in South Kazakhstan) (WNA, 2015; Seredkin and Bergen, 2013a, 2013b), which is comparable to large conventional uranium mines (Fig. 3).

4. *In situ* recovery of metals other than uranium

Research has shown that there are thermodynamic conditions suitable for leaching a broad spectrum of elements using solutions based on sulphuric acid or other solvents, with or without additional oxidants: copper, gold, silver, zinc, cadmium, lead, manganese, lithium, molybdenum, selenium, vanadium, scandium, yttrium, rare earth elements,



ISR was developed independently in the former Soviet Union Ukraine, 1959; Uzbekistan, 1960s) and the U.S.A. (Wyoming, 1958) using similar engineering and technological approaches

ISR mining ramp up the USSR (Uzbekistan, Kazakhstan) and USA (Wyoming, Texas)

New ISR mines in Bulgaria, Czechoslovakia and China

Period of major sandstone type deposits (uranium deposits most suitable for ISR) discoveries wordwide

Stagnation period in uranium industry

New small ISR projects in Russia and Australia

ISR production at existing mines in Kazakhstan and Uzbekistan

ISR mines closure in the USA, Europe

ISR mining boom in Kazakhstan (8 new mines)

New ISR mines in Uzbekistan, USA, Russia, Australia

New ISR mines in Kazakhstan, USA, Australia, Russia, Uzbekistan

ISR production share increased to 51% of World uranium production in 2015.

The capacity of ISR mines reached to conventional mines capacity

Fig. 2. ISR historical overview in the uranium industry (Boytsov, 2014; WNA, 2015 with improvements).

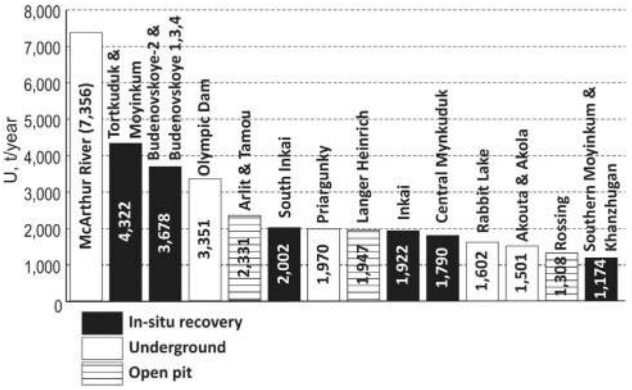


Fig. 3. The biggest uranium mines in the world in 2014 (WNA, 2015).

indium, beryllium, chromium, gallium, nickel, and cobalt (Laverov et al., 1998; O'Gorman et al., 2004).

Copper is the most popular commodity (after uranium) that is mined by ISR (Table 1). There are references to primitive forms of *in situ* leaching of copper in Roman times, and maybe even long before that in China (O'Gorman et al., 2004).

The San Manuel copper mine in Arizona is the best known copper mine exploited by ISR (O'Gorman et al., 2004). The oxide cap at the surface of San Manuel was, to a large extent, removed by open pit mining. This cap was underlain by a zone of mixed oxide and sulphide mineralization, grading to primary sulphide ore at depth. ISR was used on remnant material in the pit walls, around undergoround workings (and on low-grade dumps) (O'Gorman et al., 2004).

About 50% of the ISR copper produced at San Manuel was recovered from solutions collected from the stopes below, the remainder from solution recovery wells. Industry observers are comfortable that the ISR project at San Manuel was environmentally sound (O'Gorman et al., 2004). The capacity of ISR production reached 11,000 t Cu/yr in 1990 (Briggs, 2014). The San Manuel Mine is now closed.

In the 1970s and early 1980s an *in situ* leaching project was carried out to extract copper from oxide ores at Miami, Arizona. This *in situ* leaching project operated for 7 years and closed down in 1982 (O'Gorman et al., 2004).

ISR trials were carried out at several sites near Mount Isa, Queensland in the 1970s (O'Gorman et al., 2004). The Gunpowder Mine, located north of Mount Isa in Queensland, has used ISR technology to extract copper. Leaching or solvent extraction of broken ground (fragmented through blasting) at Gunpowder commenced in the early 1990s. Due to the lack of confining strata (the system is not sealed by impermeable clay units), the treatment liquor tends to be lost to the somewhat alkaline surrounding rock, which in turn neutralises the acid. Also the blasting tends to be inconsistent leading to variable particle size, thus inadequate or inconsistent surface area is exposed for leaching (Kay,

Table 1
Mines and projects mined by ISR.

Commodity and mines		Type	Action	Country
Li	Clayton Valley	Brine	Mining	USA (Nevada)
Li	Extensively	Brine	Mining	Chile
Zn	Salton Sea	Brine	Mining	USA (California)
Cu	Silver Bell	Oxide	Mining, closed	USA (Arizona)
	San Manuel	Oxide, mixed	Mining, closed	
	Miami (Pinto Valley)	Oxide, porphyry	Mining, closed	
	Florence	Porphyry	Pilot test	
	Casa Grande	Porphyry	Pilot test	
	Safford	Porphyry	Pilot test (hydro-fractured)	
	Mount Isa	Oxide	Mining, ISR closed	Australia (QLD)
	Gunpowder	Oxide	Pilot test	
	Mutooroo	Oxide	Pilot test	Australia (SA)
	Naciomientos	Sandstone	Pilot test	Cuba
	Chuquiquamata	Palaeochannel	Pilot test	Chile
	Mopani	Oxide	Mining	Zambia
	Gumeshevskoye	Oxide, Mixed	Mining	Russia (Ural)
	Levikha	Oxide, Mixed	Pilot test	
Cu, Zn, Au	Vostochno-semenovskoye	Oxide	Mining	Russia (Ural)
Au	North-Western Territories	Tails	Mining, closed	Canada
	Gagarskoye	Oxide	Mining	Russia (Ural)
	Maminskoye	Oxide	Mining	
	Dolgy Mys	Oxide	Mining	
	Verkhoturskoye	Oxide	Pilot test	
	Kirovogradskoye	Pyrite ash	Mining	
	Egorievskoye (Lapinsky)	Oxide	Pilot test	Russia (Siberia)
	Fartovaya	Placer	Pilot test	Russia (Ural)
	Verkniy Vels	Placer	Pilot test	
Ni	Tochilnogorskoye	Silicate	Pilot test	Russia (Ural)
	Rogozhinskoye	Silicate	Pilot test	
	Kungurskoye	Silicate	Pilot test	
Re	Bukinai, Kanimekh, Meylysay	Roll front sandstone	Pilot test (by-product with U)	Uzbekistan
	Karamurun, Zarechnoye			Kazakhstan
V	Kanimekh	Roll front sandstone	Pilot test (by-product with U)	Uzbekistan
	Zarechnoye			Kazakhstan
Se	Kanimekh	Roll front sandstone	Pilot test (by-product with U)	Uzbekistan
	Karamurun			Kazakhstan
Sc	Bukinai, Kanimekh	Roll front sandstone	Pilot test (by-product with U)	Uzbekistan
	Karamurun, Zarechnoye			Kazakhstan
	Dalmatovskoye	Palaeochannel sandstone	Pilot test and construction a commercial plant (by-product with U)	Russia (Transural)
Y, REE	Bukinai	Roll front sandstone	Pilot test (by-product with U)	Uzbekistan
	Zarechnoye, Uvanas, Kanzhugan, Moiynkum			Kazakhstan
	Dalmatovskoye	Palaeochannel sandstone		Russia (Transural)

Sources: O'Gorman et al., 2004; Laverov et al., 1998; Dokukin and Samoilov, 2009; Gurov et al., 2011.

1998). In the opinion of the authors, better management of leaching solution hydrodynamics, based on the latest achievements of the uranium industry, could eliminate the negative effects of the lack of aquicludes.

The Gumeshevskoye Copper Deposit in the Ural Mountains of Russia, was mined over nearly 300 years. It was proposed to recommence mining oxidised mineralisation by open pit. However, despite all efforts, feasibility studies concluded that conventional mining of the oxidised mineralisation at Gumeshevskoye by open pit would be unprofitable (Zabolotsky et al., 2008). An ISR mine was selected instead and has operated since 2004 with annual production of 5000 t of copper (Zabolotsky et al., 2008). The copper grade in pregnant solutions is 1–4 g/l, extraction is 40–120% (extraction >100% due to leaching copper outside estimated mineralised bodies). The capacity of ISR production reached 5000 t Cu/yr.

During the late 1980s, water pumped from underground workings of a gold mine in the Northwest Territories, Canada was found to contain low grades of gold. Seepage of very weak cyanide solution from an overlying tailings impoundment had found its way into the mine workings and resulted in leaching of some gold. The water was pumped from underground and used as process water in the mill resulting in incremental gold recovery. So, the first known commercial *in situ* leaching of gold was involuntary (O'Gorman et al., 2004).

The western world's first deliberate *in situ* gold mine was proposed at Eastville, central Victoria in the early 1980s. The project planned to inject alkaline cyanide into the "deep leads", an underground porous paleoalluvial formation. Both the community and regulators expressed concerns about the possibility of groundwater contamination arising from the use of cyanide in the rural farming area. After some initial pump and dye tracer tests, regulatory approvals were denied (O'Gorman et al., 2004).

ISR was successfully used in 1994 on the Gagarskoye Gold Deposit in the Ural Mountains region (Russia) (Zabolotsky et al., 2008; Dokukin and Samoilov, 2009) for leaching of gold-bearing regolith. A combined method was used for gold leaching (Fig. 4) (Zabolotsky et al., 2008):

- Infiltration of leaching solutions in the waterless zone above the water table using trenches and collection of pregnant solutions at the top of the water table; and,
- Conventional ISR (filtration) below the water table.

The grades of gold in the pregnant solutions reached 0.5 mg/l and extraction of gold from mineralised body up to 70% (Zabolotsky et al., 2008).

The successful experience of *in situ* recovery of gold at the Gararskoye Deposit promoted development of mining by ISR to other gold deposits in weathered regolith and deep placers (Table 1) (Dokukin and Samoilov, 2009). The total gold produced by ISR has reached 1 t, since the early 1990s (Dokukin and Samoilov, 2009).

Pilot tests of ISR for nickel were successful for some silicate nickel deposits (Table 1) with concentrations of nickel in pregnant solutions reaching 1 g/l and extraction from mineralised bodies achieving up to 70–75% (Gurov et al., 2011).

Pilot tests of ISR of gold, copper and zinc were carried out on tails and pyrite ash (after acid production) in the Urals (Russia).The ISR mine at the Kirovogradskoye technogenic deposit is currently in production. The ISR processing of the tails and pyrite ash is also useful for remediation of the tails and ash, not only for extraction of gold, copper or zinc.

Scandium, rhenium, rare earth elements, yttrium, selenium, molybdenum, vanadium were leached *in situ* as by-products in pilot tests at the uranium deposits in the 1970s–1980s (Table 1) with the following results (Laverov et al., 1998):

- Scandium—average grade in the pregnant solutions 0.2–1 mg/l with extraction from mineralised body up to 25–50%;
- Rhenium—average grade in the pregnant solutions 0.2–0.8 mg/l with extraction from mineralised body up to 20%;
- Rare Earth and Yttrium—average grade in the pregnant solutions 15–30 mg/l;
- Selenium—average grade in the pregnant solutions 100–5000 mg/l with extraction from mineralised body up to 35%;
- Molybdenum—average grade in the pregnant solutions up to 240 mg/l with extraction from mineralised body up to 80%;
- Vanadium—average grade in the pregnant solutions up to 500 mg/l with extraction from mineralised body up to 85%;

As noted above, at Dalur (an ISR uranium mine in Russia) a processing plant is being constructed to extract scandium and rare earths as by-products at a full industrial scale from the uranium pregnant solutions.

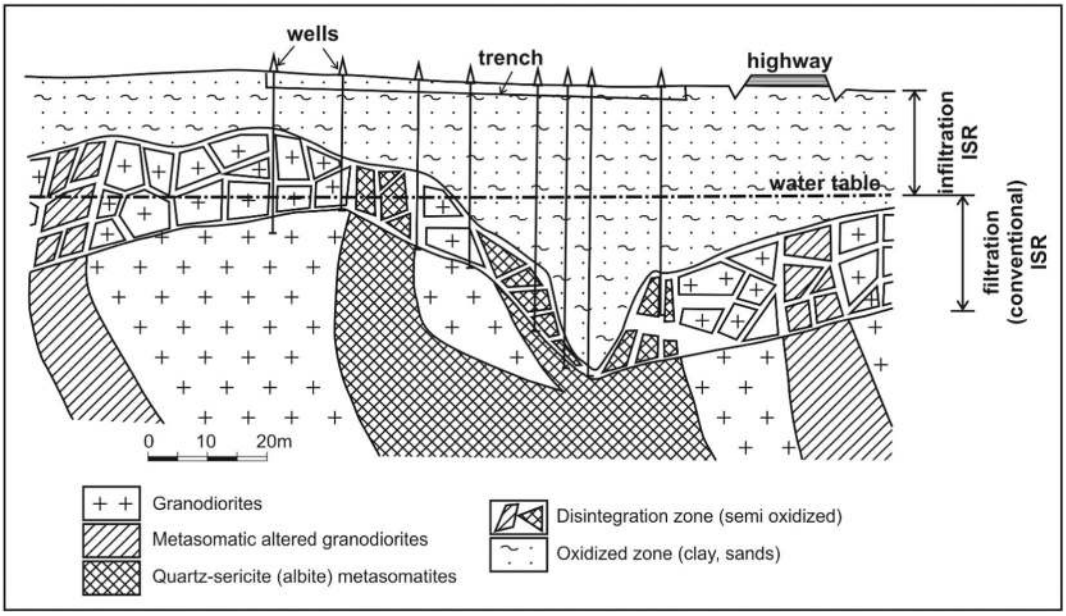


Fig. 4. *In situ* recovery of gold at the Gagarskoye deposit (Zabolotsky and Dokukin, 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

More recent advances in *ISR* of non-uranium elements (O'Gorman et al., 2004; Zabolotsky and Dokukin, 2009; Laverov et al., 1998) suggests a more widespread adoption of this ISR should be considered (Fig. 5) due to:

- Improved technology
  - o Using diverse leaching reagents not only sulphuric acid and bicarbonate, but also thiosulphate, hypochlorite, acidified chlorine, and thio-urea instead cyanides for gold leaching, as well as sulphites of sodium or potash for some other elements;
  - o Using oxidants: oxygen gas, hydrogen peroxide, sodium peroxide, sodium nitrite or nitric acid;
  - o Leaching elements below water table by conventional filtration method and above water table from waterless rocks by the infiltration method with collection of pregnant solutions at the surface of the water table; and
  - o Use of natural permeability and the creation of artificial permeability by blasting and hydro-fracturing (for example, at Mount Isa).

- Application to new types of deposits only amenable to ISR;
- Its use on technogenic deposits (tails, ash, flooded underground mines); and,
- The increasing dissemination of knowledge gained from the use of ISR in uranium mines.

As discussed above, ISR has been used for a wide spectrum of commodities and different types of deposits. But ISR has not yet become common in the mining industry due to insufficient experience with the technology, and a lack of understanding of the geological environments amenable to ISR implementation.

The authors believe that the extensive successful experience obtained from ISR uranium mining, coupled with the knowledge gained in the application of heap leaching in the gold mining sector, and in hydraulic fracturing ("fraccing") from the petroleum industry (also used for copper deposits at Gunpowder and San Manuel), together with the economic and environmental benefits described below, provide the foundations for a greater use of ISR in the near future (Fig. 5).

5. Geological features of deposits suitable for mining by *in situ* recovery

ISR can allow profitable exploitation of deposits with low grades of metals and/or small resources unsuitable for conventional mining.

There are two critical parameters that must be met for a deposit amenable to ISR:

- mineralisation must be located in permeable environment; and,
- the lixiviant should be suitable for selective leaching of a specific component from the deposit.

Permeability is the most critical parameter for ISR (Table 2). The lixiviant must be able to move between injection and pumping wells/stopes. This is possible both below the water table by filtration, and above the water table by infiltration (Fig. 4). In the latter case the level of water table should be close to sites of injection/surface (Table 2). The most typical permeability for ISR is 1–5 m/day.

The most favourable geological situation for ISR is an artesian or confined aquifer, for example sandstone-hosted uranium deposits in South Kazakhstan. Low permeability (<0.3–0.5 m/day) is not prohibiting factor for ISR if fracturing can be applied to artificially increase permeability.

Variability of permeability is also important for ISR and can lead to formation of stagnant, non-leaching, zones and/or channelling of solutions. The management of leaching and the correct installation of screens in the injection and pumping wells can help to solve this issue.

A more critical situation is when the permeability of the mineralised rocks is much less than in surrounding waste rocks; ISR is not applicable in these situations.

Selective leachability of target compounds is the second most critical parameter for ISR (Table 2). Leaching of harmful components or strong leaching of rock-forming elements can be a serious obstacle to using ISR. Correct selection of lixiviant and oxidant, as well as calibration of the leaching and acidification regime is important for dynamics of leaching and extraction of metals.

The distribution and style of mineralisation – the location and exposure of target mineral grains – strongly affects leachability (Table 2). Location of ore minerals inside inert minerals is a prohibiting factor for ISR. The most favourable positions for ore minerals is in open pores, fissures, in strongly altered rocks. The absorption properties of rocks is the critical parameter also. ISR in rocks with high absorption such as peat or coal is impossible (Table 2).

Other characteristics of mineralisation and host rocks can affect the profitability of ISR projects or prevent the use of ISR at the current level of technology development (Table 2). For example, the need for aquicludes, especially below mineralisation, was a critical parameter in the earlier years of ISR development. However, evolution of the technology now allows the Budenovskoye Deposit, which does not have continuous aquiclude below the mineralised bodies, to be one of the best ISR uranium projects in the world (Seredkin and Bergen, 2013a, 2013b).

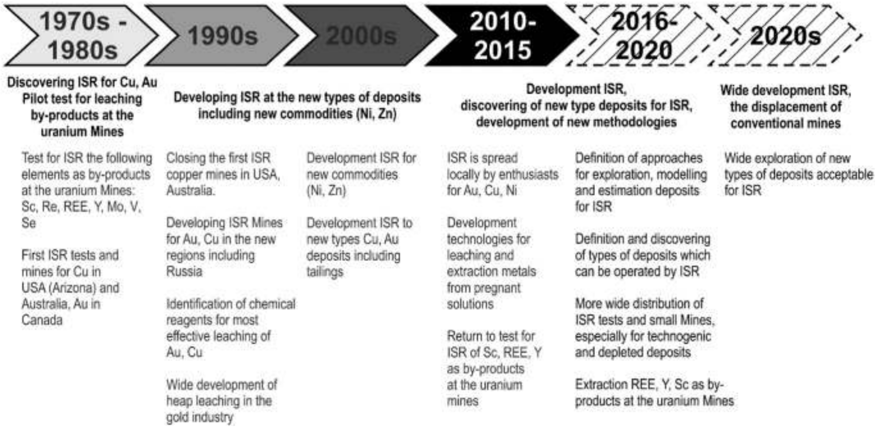


Fig. 5. ISR historical overview in the non-uranium industry (using information from O'Gorman et al., 2004; Zabolotsky and Dokukin, 2009; Laverov et al., 1998; Gurov et al., 2011).

Table 2
Parameters for assessment of deposits suitability for ISR.

Parameters	Favourable	Probably favourable	Unfavourable
Critical parameters			
Hydrogeological conditions	Artesian or confined aquifer	Below water table, waterless above water table with water table level close to surface	Waterless mineralisation with deep water table from the surface
Permeability	High permeability (>5–10 m/day)	Moderate permeability (1–5 m/day)	Low permeability (<0.5–1 m/day)
	Homogeneous permeability	Uneven permeability	Permeability of mineralisation much less than waste rocks
Leachability	Selective leachability of useful compounds without harmful components	Selective leachability of useful compounds without adsorption harmful components	No selective leachability of useful compounds
Location of mineralisation	In fissures, open pores	Between grains of other minerals	Predominantly included in other minerals (non-leachable)
Chemical composition	No minerals with high adsorption	Low grade of minerals with high adsorption	High grade of minerals with high adsorption
Important parameters			
Depth of mineralisation	Shallow deposits (<150 m)	Deep deposits (150–750 m)	Very deep deposits (>750–900 m)
Morphology of mineralisation	Tabular deposits	Lightly pitching deposits	Steeply pitching deposits
Thickness	High thickness (>5–10 m)	Moderate thickness (2–5 m)	Thin thickness (<2 m)
Grades	Low grades	Low-moderate grades	High grades
Grade-thickness	High grade-thickness	Moderate grade-thickness	Low grade-thickness
Type of mineralisation	Oxidised, mixed	Mixed, reduced/primary	Reduced/primary
Distribution of mineralisation	Equally distributed	Uneven distribution	Absolutely uneven distribution
Size of mineralisation	Finely-dispersed, amorphous	Fine-/medium-crystalline	Coarse crystalline
Chemical composition	Low acid/reagent consumption mineralisation	Moderate acid/reagent consumption mineralisation	High acid/reagent consumption mineralisation
	No reducing agents	Low/moderate grade reducing agents	High grade reducing agents
Physical condition	Unconsolidated low clay sands	Low-medium- consolidated sands, moderate clay sands	Strong consolidated or permanently frozen sands
	Strong disintegrated rocks (incl. artificially)	Moderate disintegrated rocks (incl. artificially)	Monolithic hard rocks, clays, permanently frozen rocks
Aquiclude	Above and below mineralisation	Below mineralisation/no aquiclude	–
Environmental/location parameters			
Location	Developed region and free area	Undeveloped region	Usable area
Landscape	Plane with rare orographic network	Hilly relief	Mountains, strong orographic network
Environmental	No water intakes	No water intakes close to deposit	Water intakes close to deposit

When undertaking resource estimation for deposits to be exploited using ISR, it is important to model mineralisation and select "cut-offs" using the grade-thickness product (GT), or productivity, of mineralised bodies, rather than the simple grade distribution of mineralisation.

Productivity is defined as the product of the mineralised body thickness, the grade of mineralisation (in per cent), the bulk density, and a factor of 10 (Seredkin and Bergen, 2013a, 2013b, 2014, 2015). Extraction level and the dynamics of leaching depend on more on GT than on grades (Fig. 6) (Seredkin et al., 2014; Boytsov et al., 2014).

Mineralisation with higher thickness and lower grades is more favourable for ISR than mineralisation with low thickness and high grades. For example, the mineralised interval with 0.04% U × 10 m is better for ISR than 0.10% U × 3 m (Seredkin et al., 2014).

Parameters of mineralisation/deposits, shown in the Table 2, may be used during research, evaluation, exploration and resource estimation stages for assessment of applicability of ISR.

6. Environmental aspects of ISR

ISR allows the extraction of mineralisation with minimal disturbance to the existing natural conditions. In contrast to underground and open pit mining, there are:

- no large open pits;
- no rock dumps and tailings storage;
- no dewatering of aquifers;
- much smaller volumes of mining and hydrometallurgical effluents (that could contaminate the surface, air and water supply sources); and,
- no exhaust pollution (IAEA, 2001; O'Gorman et al., 2004).

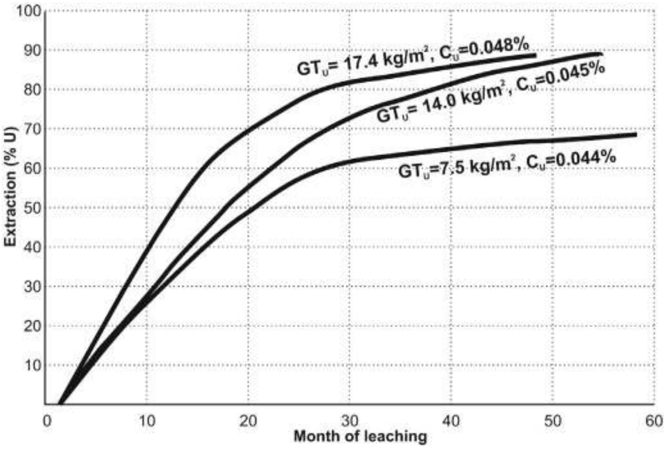


Fig. 6. Relationship between leaching dynamics and productivity (or GT) at the Budenovskoye Uranium Deposit in Kazakhstan (Seredkin et al., 2014; Boytsov et al., 2014).

As a result, the impact of ISR projects on the environment is much less than for conventional mining methods, as long as projects are properly planned, operated and closed, using best practice.

ISR mines successfully operate in range situations, including in close proximity to populated areas, and of different climatic regions. For example, the Dalur ISR Mine (Russian Federation) operate in the agricultural Transural region, and Gagarka Mine in the populated area near the water intake point for the town of Zarechny and adjacent to the Yekaterinburg–Tyumen highway. Khiagda deposit (Russian Federation) is operated in a region with permafrost whereas deposits in Kazakhstan and Australia in a hot desert.

In ISR the primary risk of contamination for soils, surface waters and aquifers, is from the reagents used for leaching, and from the metals in pregnant solutions. Although the risk of such contamination is local, it has the potential to impact the regional economy, flora and fauna.

Therefore, ISR operations should remain under strict surveillance both during the ISR process and during the subsequent reclamation of the site. In some cases (especially in populated areas) it will be necessary to restore the contaminated groundwater and/or long-term monitoring programmes must be established to ensure that the contamination does not spread into uncontrolled aquifers or other areas (IAEA, 2001).

The most serious environmental risk from ISR operations is surface contamination and damage to soils. Surface contamination may result from leaching solution leaking from defective pipelines, spills from open injection wells, pumping of wells for cleaning or sampling, or when production solutions are just dumped on the ground instead of into special reservoirs (Mudd, 1998). Contamination during an ISR operation will be minimal with good environmental control services. Nevertheless, there will likely be some degree of surface contamination and planning for final clean-up should be included from the outset (IAEA, 2001).

Acid leaches (usually with anions such as SO_4^{-2}) are the most widespread ISR approach (IAEA, 2001). In a properly designed wellfield, the extent of the halo of leachant is limited by hydrodynamic balance within the wellfield.

In these cases, groundwater contamination takes place within a relatively small zone (usually $<$100 m) of hydraulic influence near leaching wells and does not move along the stratum (away from the wellfield) (Fig. 7) (IAEA, 2001). Monitoring wells around of ISR polygons allows control of conditions within the aquifer.

When ISR is finished and the artificial cone of depression around the production well is abandoned, the hydrogeology returns to the natural flow of groundwater. This can cause contamination to move away from the ISR site for distances up to several hundred metres (IAEA, 2001).

In situ permeability and the adsorption/capacitive properties of rocks should be determined and a hydrogeological model created prior to commencement of ISR operations. This model will allow an estimate of the likely migration of residual solutions within groundwater post operations (IAEA, 2001).

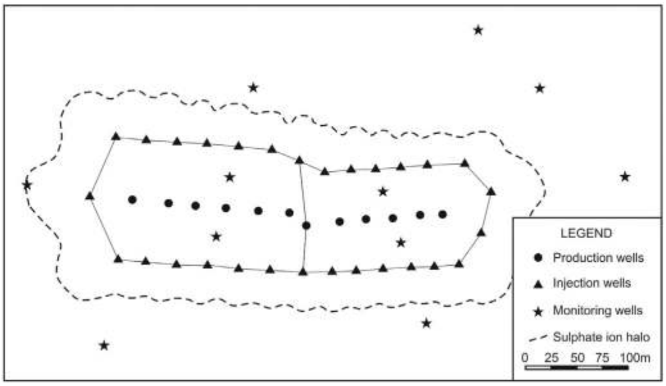


Fig. 7. Observation of aquifer by monitoring wells (Valliant and Bergen, 2012; IAEA, 2001).

Decisions on the need for cleaning an aquifer is taken on the basis of these studies and on the availability of water intakes. Cleaning of aquifers may be a condition of permitting, and may involve active cleaning and/or self-cleaning, with monitoring required for periods up to ten years (Fig. 8).

7. Economic attributes and advantages of ISR

The uranium industry shows that ISR is the cheapest source of uranium. The production cost (OpEx) of uranium is less than US$40 per pound U_3O_8 at the most of the deposits operated by ISR (Fig. 9). These deposits are profitable while uranium prices are low. The underground mines at Olympic Dam in South Australia that produces uranium as by-product, and at McArthur River in Canada with extremely high uranium grades ($\approx$15%) compete with ISR deposits for low production costs.

Capital investments (CapEx) for ISR mines are significantly (up to several times) less than for conventional open pit or underground mines (Fig. 9). The average CapEx for 1000 t of uranium per year at ISR mines is US$80 million, including US$48 million for processing plant (Boytsov, 2014). These capital investments can be stretched in time by a gradual increase of the capacity of the mine.

As a result, the following types of uranium mines are currently economic:

- ISR mines (*e.g.* mines in South Kazakhstan);
- underground mines with extremely high grades of uranium (*e.g.* McArthur, Cigar Lake in Canada);
- open pit mines in moderate climate conditions with quite high production (*e.g.* Ranger in Northern Territory, Rossing and Langer Heinrich in Namibia); and,
- where uranium is recovered as a by-product (*e.g.* Olympic Dam in South Australia).

In comparison to other types of mining operations (Table 3), ISR offers a number of distinct advantages:

- Lower development costs for the mine, processing plant and infrastructure (Fig. 9);
- The ability to start production at low capital cost with a following increase in production; this allows use of profits from cash flow to fund development of the mine instead using debt financing (Fig. 10); and,
- Greater flexibility in production capacity (easier reduction of capacity during lower price periods and increased capacity during higher price times).

Examples of economic parameters of the non-uranium ISR deposits are shown in the Table 4.

The economics of ISR mines primarily depend on following the parameters:

- Flow rate capacity of the wellfields (input capacity of injection wells and extraction capacity of production wells);
- Concentration of extracted component(s) in pregnant solutions;
- Overall level of extraction of mined component(s); and,
- Ratio of Liquid to Solid (L:S) required to achieve the desired extraction of the mined component(s). This ratio is calculated based on volume of solutions passed through the operational block over the whole period of operation and on the tonnage of the operational block.

L:S ratio is a key parameter for ISR mines and depends on the dynamics of leaching. The smaller this ratio, the better the economy of the project.

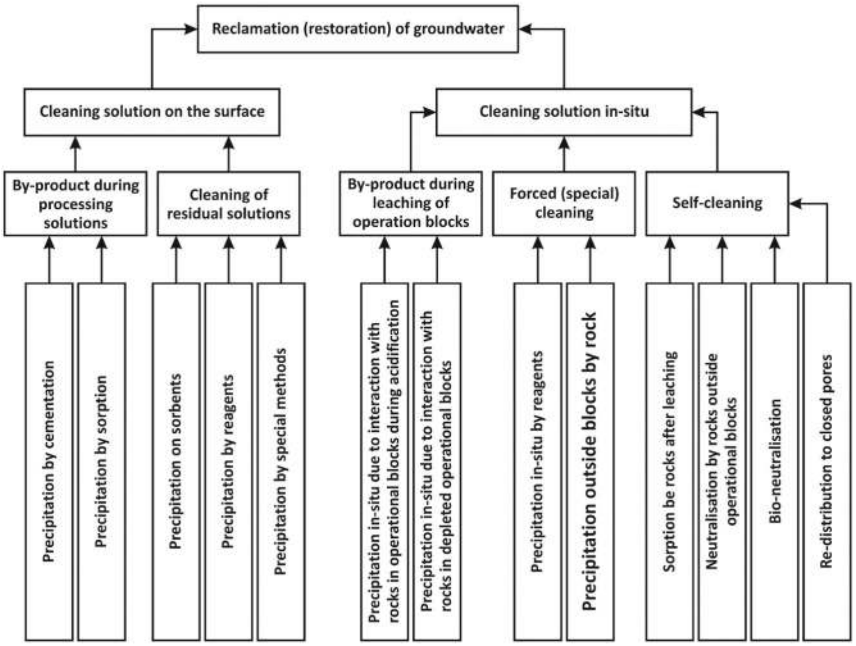


Fig. 8. Approaches to cleaning of solutions in ISR.

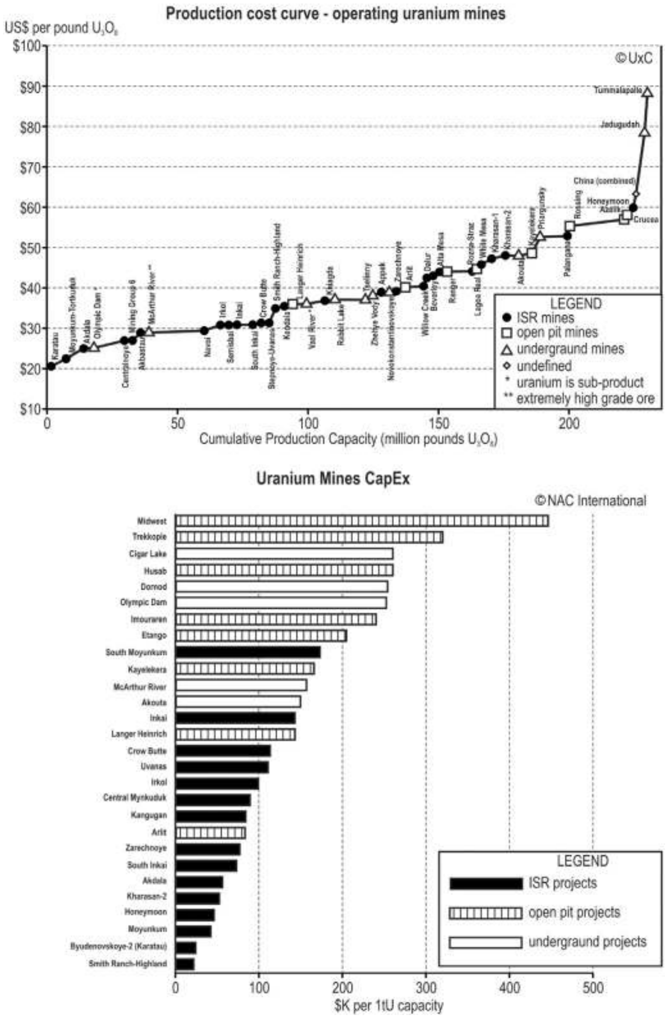


Fig. 9. Comparison of economical parameters for ISR mines with conventional open pit and underground mines on the example of the uranium industry (Boytsov, 2014 with improvements).

The flow rates of solutions and the concentrations of leached component(s) in pregnant solutions are related with to each other. Concentrations of leached components can be increased by decreasing the flow

Table 3
Comparison of different mining operations (underground, open pit and ISR).

Parameters	Underground	Open pit	Open pit with heap leaching	*In situ* recovering
Exploration				
Exploration	+	+	+	+
Mining				
Removing overburden		+	+	
Developing pit		+	+	
Shaft	+			
Stopes	+			
Ventilation	+	+	+	
Mining equipment	+	+	+	
Mining complex on surface	+	+	+	
Electricity	+	+	+	+
Dump	+	+	+	
Operational wells				+
Pumps				+
Pipelines				+
Mining of ore	+	+	+	
Dewatering	+	+	+	
Reagents				+
Acidification				+
Pumping				+
Leaching				+
Processing				
Processing plant	+	+	+	+
Crushing, breaking	+	+	+	
Separation, flotation, …	+	+		
Hydrometallurgical processing	+	+		
Sorption, desorption			+	+
Precipitation	+	+	+	+
Tails	+	+		
Rehabilitation				
Reclamation	+	+	+	+

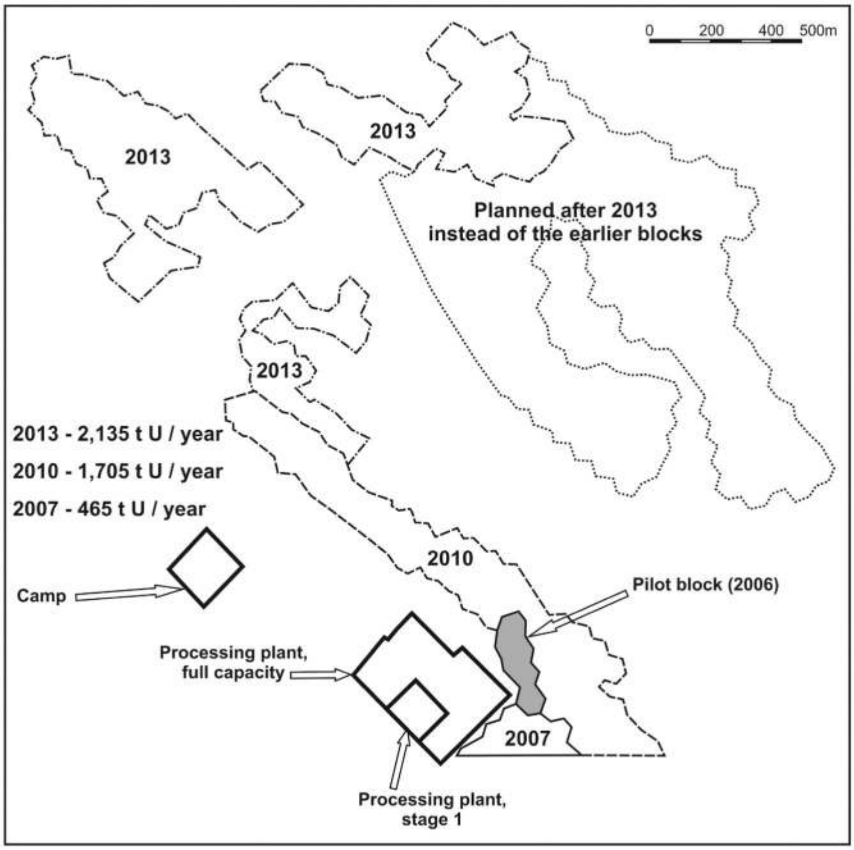


Fig. 10. Gradual development of the Budenovskoye-2 (Karatau) Mine, Budenovskoye Deposit in Kazakhstan (Valliant et al., 2007; Valliant and Kyle, 2010; Seredkin and Bergen, 2013a, 2013b).

rate of solutions, but at the cost of an increased time to reach the desired extraction level of mined component(s). This means that production should be undertaken from a larger number of blocks with a concomitant increase mining costs. Optimising these different parameters if critical for successful ISR operations.

The concentration of metals in pregnant solutions is not stable during operation of blocks (Fig. 11). Concentration reaches the maximum relatively quickly followed by a gradual decrease. The shape of the curve depends on the leachability of the mineralisation. The economics are estimated based on the average concentrations, which achieved by combination of blocks in the early and late stages of mining.

The technological schemes for leaching and processing of solutions are approximately same for different commodities (Fig. 12). This feature of ISR operations can be used to provide an estimation of the potential financial performance of new ISR projects based on the well-known economics of established uranium ISR Mines.

It should be kept in mind that a more specific and detailed assessment of the economics should take into account many parameters, including:

- depth of mineralization;
- costs of leaching reagents;
- costs of processing, including costs of resins and demonstrated processing paths to profitably recover the target metals; and
- existing infrastructure.

Based on the economics of known ISR uranium projects, the following parameters have been approximated:

- break even cut-off concentrations for metals in pregnant solutions;
- capital costs and full production costs (normalised to unit of commodity);

Table 4
Economical parameters for gold and copper ISR projects.

Parameters	Commodity	Pregnant solution	Capacity	CAPEX	FULL OPEX
Gagarka	Gold	0.2–0.6 mg/l	90 kg/yr	0.4 M$	7 $/g
Kirovogradskoye	Gold	0.33 mg/l	686 kg/yr	3 M$	14 $/gr
Gumeshevskoye	Copper	1–4 g/l	5000 t/yr	20 M$	2700 $/t

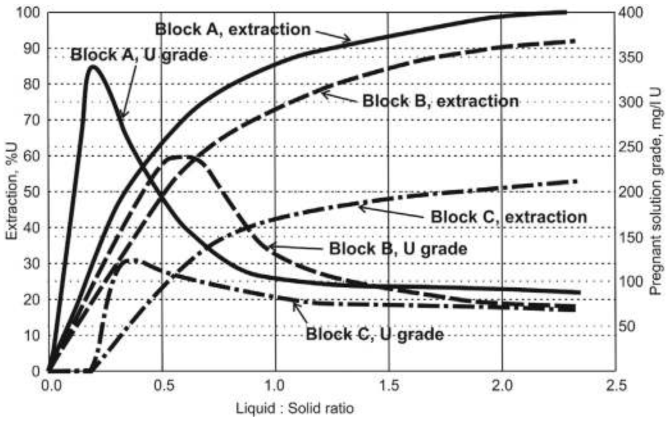


Fig. 11. Dependence of uranium grades in pregnant solutions and extraction level on L:S ratio. (≈ time of leaching) for several blocks of Budenovskoye deposit (Seredkin and Bergen, 2013a, 2013b).

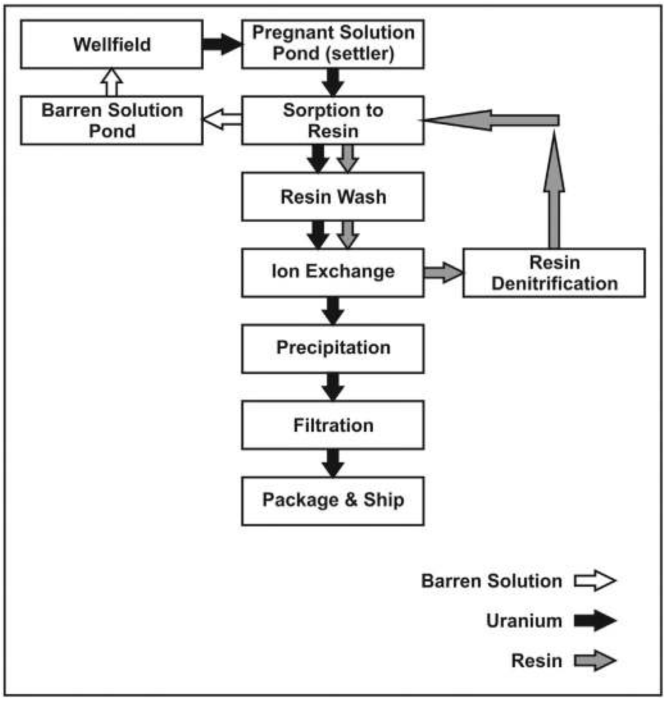


Fig. 12. Typical technological scheme of production and processing of solutions for ISR projects (Seredkin and Bergen, 2015).

- cut-off grades and productivity cut-offs for use in resource estimation for ISR projects.

The outcomes of these approximations are shown in Table 5 and Table 6.

For estimates of capital cost, South Inkai, one of the largest ISR Mines, was used to define the upper range, while the Budenovskoye-2 (Karatau) Mine was used to estimate the lower range of capital cost for ISR projects.

The following parameters from ISR Uranium Mines are used as proxies for other economic aspects of ISR projects (more detail information in the reports Seredkin and Bergen, 2014; Seredkin and Bergen, 2013a, 2013b):

- flow of solutions;
- annual production;
- breakeven cut-off grade uranium;
- extraction uranium from solutions;
- capital cost;
- Liquid to Solid ratio;
- operating cost and,
- cost for development of well field $/lb.

Capital costs, operating costs and full production costs were estimated based on concentrations in pregnant solutions reached in pilot tests or in operation of ISR mines (see above).[3]

Cut-off grades for estimation of Mineral Resources were estimated based on breakeven cut-off grades in pregnant solutions for different L:S ratios and levels of extraction (Table 6) for various of commodities using optimistic conditions (L:S of 3, 90% extraction; readily leachable mineralization) through to suboptimal conditions (L:S of 7, 50% extraction; poorly leachable mineralization).

Gold, nickel, copper, vanadium, and selenium could be profitably mined by ISR based on estimated levels of metals in productive solutions, whereas molybdenum, rhenium, scandium and rare earth are only likely to be mined as by-products with uranium, because predicted concentrations in pregnant solutions are not enough for profitable operations. However, it is possible that new types of deposits could be discovered where these metals could be extracted in their own right, rather than as by-products.

The following cut-off grades are suggested as guidelines for selecting mineral deposits suitable for ISR (Table 6), taking into account the criteria shown in Table 2:

- Copper → 0.2%;
- Gold → 0.25–0.30 ppm;
- Nickel → 0.1%;
- Molybdenum → 0.075–0.08%;
- Scandium → 2.5–3 ppm;
- Rhenium → 3.5–4 ppm,
- Vanadium → 0.05%;
- Selenium → 0.025%; and,
- Rare Earth Elements → 0.05–0.06%.

Furthermore it should be noted that the metal endowments of deposits suitable for ISR with low grades can be quite small, for example, uranium from 5000 t, gold from 1000 kg, copper and nickel from 15,000–25,000 t.

Investigation of leaching of other elements will allow the estimation of criteria to define the economic parameters for these new deposit types.

8. Special requirements for exploration, mineral resource estimation and development of ISR projects

Exploration, estimation and development of ISR projects has some features along with the usual requirements to mining projects. Particular features of resource estimation and development of ISR projects are described in this section.

Projects for ISR should be checked for compliance with the criteria shown in the Table 2 from the earliest stages of evaluation and exploration (Table 7). Hydrogeological investigations are strongly recommended beginning with the evaluation stage. Filtration properties including permeability of rocks should be defined taking account the anisotropy of the geological environments. For example, stratified deposits should be investigated layer by layer using flow metering (Fig. 13) (Brovin et al., 1997).

Estimation of *in situ* permeability has historically been done by using common wireline tools (*e.g.* resistivity, spontaneous polarisation) as proxies for permeability following calibration of the geophysical logging by reference to hydrogeological tests (Fig. 14) (Boytsov et al., 2014; Seredkin et al., 2014). In these situations calibration should be done for each aquifer and/or mineralised hosted horizon or even parts of a horizon. However, recently the introduction of new wireline tools such as nuclear magnetic resonance (NMR) logging provides a means of direct measurement of *in situ* permeability, as well as clay:sand ratios and porosity (Al-Harbi et al., 2007).

Exploration and subsequent Mineral Resource estimation should take into account the particular aspects of ISR when considering public reporting of potential ISR operations. The JORC Code (2012) defines a Mineral Resource as 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),

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[3] Concentration of useful component in pregnant solution is one of the economical parameters, other parameters such as consumption of lixiviant, L:S ratio (dynamics of leaching), depth and morphology of mineralisation and others. But simplified indicative economic estimation gives the results comparable with factual data.

Table 5
Indicative estimation of economical parameters for ISR projects.

Commodity	Prices (US$)	Pregnant solutions			Indicative estimation of economical parameters					Ore mineralisation	
		Cut-off grade	Reached grades		Accepted options for estimation		CAPEX, MUS$	OPEX, US$	Full Production cost, $	Cut off (L:S = 3, Recovery 75%, thickness 4 m)	
		mg/l	mg/l	$/m^3	Capacity	mg/l					
Uranium	$35/lb	28	35–500	3.2–45.5	1000 t	60	60–145	$17/lb	$28/lb	0.011%	0.04 m%
Copper	$5000/t	510	1000–4000	5–20	10,000 t	2200	15–40	$1200/t	$2000/t	0.204%	0.82 m%
Gold	$1100/oz	0.07	0.5	17.7	1000 kg	0.5	7–17	$165/oz	$275/oz	0.28 ppm	1.12 mppm
Nickel	$10,000/t	255	1000	10	10,000 t	1000	40–90	$2630/t	$4400/t	0.102%	0.41 m%
Molybdenum	$13,000/t	196	240	3.1	1000 t	240	15–35	$10,960/t	$18,360/t	0.078%	0.32 m%
Scandium	$3600/kg	0.71	1.0	3.6	1000 kg	0.8	5–11	$3289/kg	$5508/kg	2.84 ppm	11.4 mppm
Rhenium	$85/oz	0.93	0.8	1.4	1000 kg	0.8	5–11	$102/oz	$171/oz	3.72 ppm	14.9 mppm
Vanadium	$20/kg	127	500	10	10,000 t	500	70–170	$5.3/kg	$8.8/kg	0.051%	0.20 m%
Selenium	$15/lb	65	150	72	1000 t	150	24–57	$8/lb	$13/lb	0.026%	0.11 m%
Rare Earth	$19/kg[a]	134	30	0.57	1000 t	30	120–285	$88/kg	$147/kg	0.054%	0.21 m%

[a] 15$/kg LREE, 50$/kg HREE and Y.

Table 6
Indicative estimation of cut-off grades and productivities for ISR projects.

Commodity	Cut-off grade, mg/l	Units	Extraction 50%			Extraction 70%			Extraction 90%		
			L:S = 3	L:S = 5	L:S = 7	L:S = 3	L:S = 5	L:S = 7	L:S = 3	L:S = 5	L:S = 7
Uranium	28	%	0.017	0.028	0.039	0.012	0.020	0.028	0.009	0.016	0.022
Copper	510	%	0.306	0.510	0.714	0.219	0.364	0.510	0.170	0.283	0.397
Gold	0.07	ppm	0.42	0.70	0.98	0.30	0.50	0.70	0.23	0.39	0.54
Nickel	255	%	0.153	0.255	0.357	0.109	0.182	0.255	0.085	0.142	0.198
Molybdenum	196	%	0.118	0.196	0.274	0.084	0.140	0.196	0.065	0.109	0.152
Scandium	0.71	ppm	4.26	7.10	9.94	3.04	5.07	7.10	2.37	3.94	5.52
Rhenium	0.93	ppm	5.58	9.30	13.02	3.99	6.64	9.30	3.10	5.17	7.23
Vanadium	127	%	0.076	0.127	0.178	0.054	0.091	0.127	0.042	0.071	0.099
Selenium	65	%	0.039	0.065	0.091	0.028	0.046	0.065	0.022	0.036	0.051
Rare earth	134	%	0.080	0.134	0.188	0.057	0.096	0.134	0.045	0.074	0.104

continuity and other geological characteristics of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge, including sampling" (JORC, 2012).

Collection of hydrogeological data, detailed lithologies, mineralogical composition and other similar investigations according Table 2 are encouraged from the earliest stages of exploration and resource estimation. Modelling of lithology along with mineralisation is strongly recommended for deposits planned for ISR operations. The transparency and materiality principles of the JORC Code require that conclusions on the suitability of ISR should be provided for any Mineral Resources proposed for exploitation by ISR, even at the Inferred Resource category.

Detailed hydrogeological investigations including cluster pump tests (hydrological test with central injection well and several observation wells, this test is very useful for investigation of hydrogeological anisotropy) and simple laboratory leaching tests (Fig. 15) are strongly recommended for estimation of Indicated and Measured resources (Table 7), especially for uncommon commodities for ISR (*e.g.* zinc).

The JORC Code defines an Indicated Mineral Resources as "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" (JORC, 2012). A geological model that includes the distribution of permeability is useful for this level of resource estimation (Fig. 16), whereas the impermeable interbeds must always be modelled.

Push-pull (or dual well) *in situ* leaching tests, without processing of pregnant solutions, is recommended for Indicated Resource estimation for uncommon geological/genetic types of deposits. Analogies can be used for typical deposits and commodities mined by ISR, for example new uranium deposits in South Kazakhstan in the same horizons within existing deposits (Mynkuduk, Inkuduk et al.) (IAEA, 2001).

A scoping study or preliminary economical assessment is an early stage evaluation of a mining project. The principal parameters for a conceptual study are mostly assumed and/or factored. Accordingly, the level of precision of capital costs ±50% (RungePinockMinarco, 2015). A series of laboratory leaching tests with different concentrations

Table 7
Special requirements for estimation and development of ISR projects.

Stage	Minimal requirements	Recommended requirements
Mineral resource estimation		
Evaluation (exploration target)	Analysis of geological structure of perspective area for compliance of criteria to ISR	Plus single hydrological tests, regional hydrological model
Inferred mineral resources	General lithological model, single hydrological tests, model of mineralisation, granulometry, mineralogical analysis	Plus single laboratory leaching tests
Indicated and measured mineral resources	Detail model of mineralisation and lithology, cluster hydrological tests, detail granulometry and mineralogical analysis, single laboratory leaching tests	Plus model of permeability, push-pull or two wells *in situ* leaching test
Engineering stage		
Scoping study	Laboratory leaching tests for different parameters, reagents and oxidants, laboratory extraction metals from pregnant solutions, hydrodynamic modelling	Plus push-pull or two wells *in situ* leaching test without processing of pregnant solutions
Prefeasibility study	Push-pull or two wells *in situ* leaching test without processing of pregnant solutions, laboratory extraction metals from pregnant solutions	Multi-wells *in situ* leaching test without processing of pregnant solutions; laboratory extraction metals from pregnant solutions
Feasibility study	Multi-wells *in situ* leaching test with processing of pregnant solutions with transition to pilot mining	

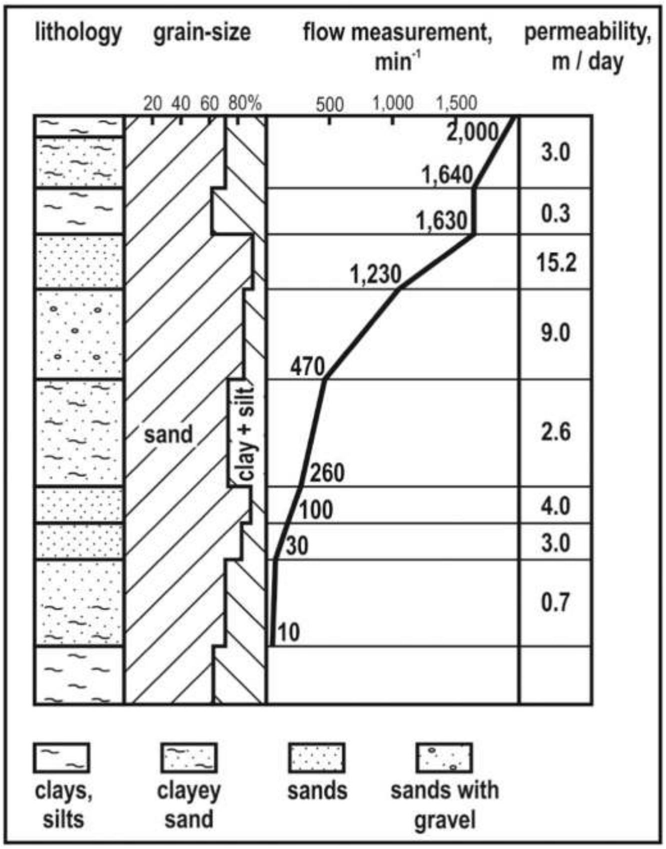

Fig. 13. Definition of permeability layer by layer using flow metering (after Brovin et al., 1997).

of reagents and oxidants should be carried out (Table 7) (IAEA, 2001). These tests are required to define:

- optimal types and concentrations of reagents and oxidants for extraction of mineral components;
- definition of maximal and average concentrations of mineral components for different conditions of leaching;
- definition of consumption of reagents and oxidants for different conditions of leaching; and
- definition of level of extraction of mineral components for different level of liquid: solid ratio.

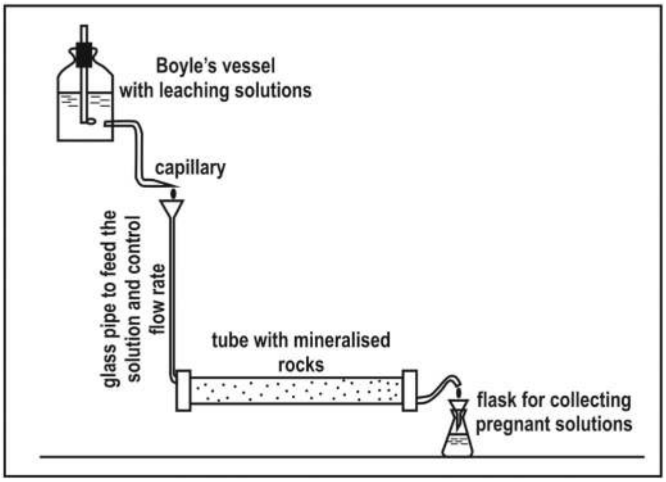

Fig. 15. Typical scheme of laboratory leaching tests (IAEA, 2001).

Note that concentrations of mineral components, and the dynamics of leaching in laboratory tests, are usually higher than in *in situ* field tests. Laboratory tests cannot take into account all the features of actual geological substrates. Therefore push-pull well tests, using the best leaching option defined in laboratory testwork, are recommended for Scoping Study work (Table 7).

Leaching metals from rocks into solution is not enough for a Scoping Study. Demonstration of the recovery of metals from the pregnant solutions is also important. For example, new technology able to profitably extract scandium from pregnant solutions was developed recently that will allow to extract scandium from the pregnant solutions in the uranium Mines of Kazakhstan (Zhivov, 2014).

Multi-well *in situ* leaching field tests (Fig. 17) is strongly recommended for Prefeasibility Study level of economical assessment (Table 7). The Canadian Institute of Mining, Metallurgy, and Petroleum (CIM, 2010) defines a Pre-Feasibility Study as “a comprehensive study of a range of options for the technical and economic viability of a mineral project that has advanced to a stage where a preferred mining method, in the case of underground mining, or processing is determined. It

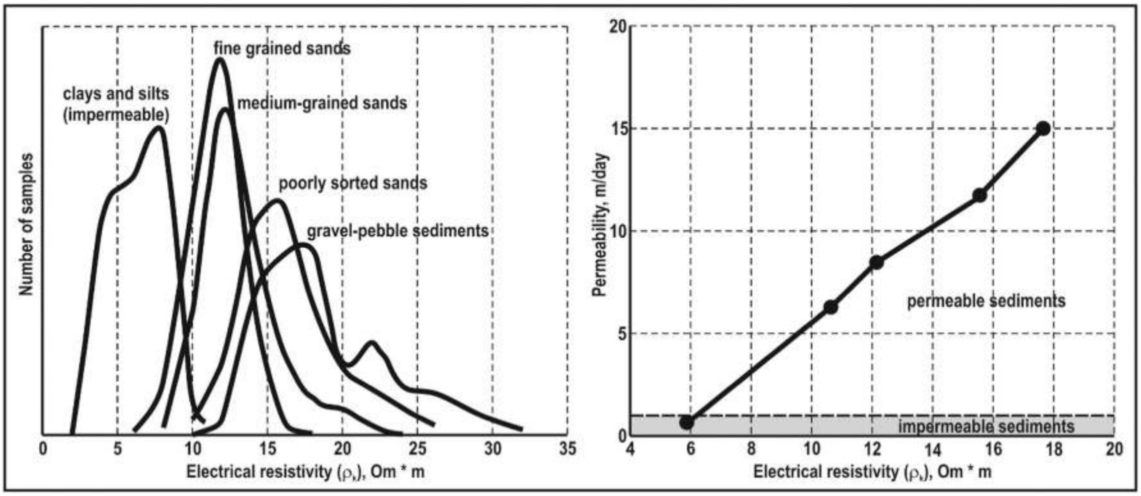

Fig. 14. Calibration of resistivity logging for definition of permeability for Budenovskoye Deposit (Boytsov et al., 2014; Seredkin et al., 2014).

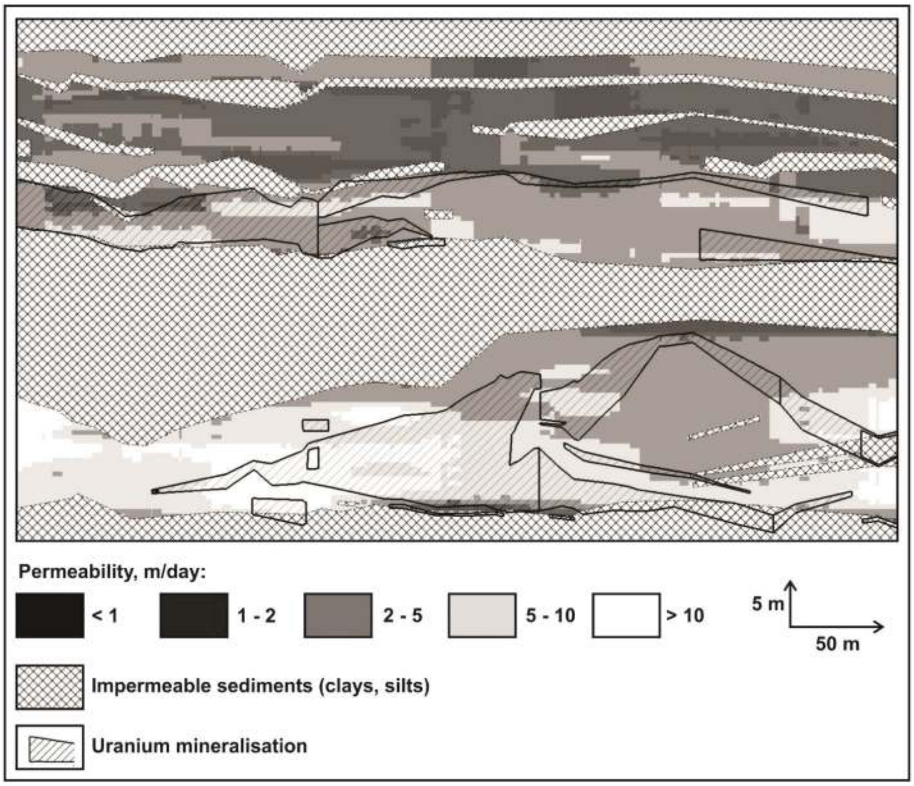

Fig. 16. Geological model with distribution of permeability for one of the uranium deposits in South Kazakhstan.

includes a financial analysis based on reasonable assumptions on the Modifying Factors and the evaluation of any other relevant factors which are sufficient for a Qualified Person, acting reasonably, to determine if all or part of the Mineral Resource may be converted to a Mineral Reserve at the time of reporting. A Prefeasibility Study is at a lower confidence level than a Feasibility Study" ±25% (RungePinockMinarco, 2015).

The progression of an ISR project from laboratory, or even push-pull tests, to multi-well *in situ* leaching field tests is the most critical step. Multi-wells *in situ* leaching field tests validate the assumptions and predictions of earlier work: geological, lithological, leaching, hydrodynamic. Refinement of wellfield modelling is the usual outcome of the multi-well testwork. Sometimes these tests are unsuccessful and the reasons for this need to be found.

Geotechnological parameters defined by multi-wells *in situ* field tests are considered reliable for Prefeasibility Studies, especially for central cells, where the influence of ground water on leaching solutions is minimal (Fig. 17).

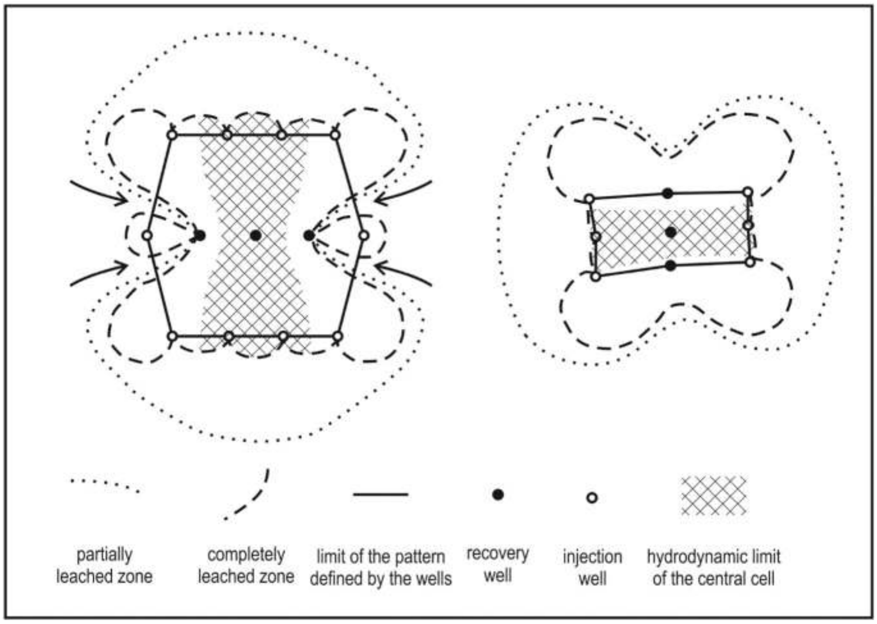

Fig. 17. Multiple well *in situ* leaching tests (after IAEA, 2001).

Several multi-well *in situ* field tests should be carried out if a deposit comprises several different mineralised horizons or geotechnological types of mineralisation.

Processing solutions in the field can be excluded from tests for Prefeasibility study, with laboratory processing solutions of considered enough.

Push-pull (or two well) tests are the absolute minimum level of work required for a Prefeasibility Study.

9. Conclusions

In situ recovery (ISR) is the one of the most effective methods available to reduce the cost of production for certain deposits or parts of deposits. One feature of ISR is transferring part of hydrometallurgical processing to mineralised bodies below the surface and directly obtaining solutions of metals.

Uranium industry is the first experience of absolutely successful using ISR for mining. Uranium production share by ISR in the World reached 51% in 2014. Experience of ISR in the uranium industry may be used for development of ISR for other commodities.

Experience of mining of Copper and Gold by ISR is successful, but in small amounts. Scandium, Rhenium, Rare Earth, Yttrium, Selenium, Molybdenum, Vanadium were leached *in situ* as by-product in pilot tests at the uranium deposits. Some other elements such as nickel, silver, zinc, cadmium, lead, manganese, indium, cobalt and other could be mined by ISL theoretically.

ISR is well suited to mining particular types of deposits, for example, some deposits which are not now economically viable by conventional mining, technogenic deposits (tails, ash, flooded underground mines), and inaccessible parts of deposits (flanks of deposits outside pits, or mineralisation below the pit floor). ISR can currently be considered an auxiliary to conventional mining, but the ongoing evolution of the ISR methodology will gradually increase the share of ISR in operations similar to situation in the uranium industry.

The two most critical geological/methodological parameters that must be met for a deposit to be suitable for ISR are:

- that mineralisation must be located in permeable environment (natural or artificial); and,
- the lixiviant should be suitable for selective leaching of a specific component from mineralised bodies of deposit.

The economic advantages of ISR include:

- Smaller costs on the development of mine, processing plant and infrastructure in comparison with conventional open pit and underground mines;
- The ability to start production at low capital cost with following increase a production. This stage allows produce a concentrate and use profitable cash flow to development of mine instead using a borrowed funds; and
- Flexibility of production capacity: reducing capacity during lower prices and increasing capacity during higher prices.

Low grades are not a critical factor for ISR. At the same time the size of deposit is much less important in ISR operations.

ISR allows to extract the ore mineralisation with minimal disturbance of the existing natural conditions. In contrast to underground and open pit mining, there are no large open pits, rock dumps and tailings storage; dewatering of aquifers; much smaller volumes of mining and hydrometallurgical effluents that could contaminate the surface, air and water supply sources. As a result, the impact of ISR on the surface environment is much less than for conventional mining methods as long as projects are properly planned, and operated and closed using best practice.

Risk of pollution of ground water is minimised if wellfield operated in hydrological balances and using special monitoring wells. Approaches for cleaning and monitoring of ground water are shown in this article.

Projects for ISR should be checked for compliance with the criteria from the earliest stages of evaluation and exploration. Hydrological investigations are strongly recommended beginning with the evaluation.

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