Overview of In-Situ Recovery for non-uranium metals

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Introduction

In situ recovery (ISR) is the one of the most effective methods to address mining costs.

The key feature of ISR is transferring a significant proportion of the hydrometallurgical processing of mineralised bodies to the subsurface, to directly obtain solutions of metals.
Opportunities - economics

- Lower Capital cost
- Lower Operation Cost
- Low production start up capital costs, and easily scalable increased production
- Generates early cash flow from concentrate production to develop the mine
- Reducing need for borrowed funds
- Flexible production capacity

![Graph showing in-situ recovery and open pit mining costs over years.](image-url)
Opportunities - environment

- Minimal disturbance of landscape
- No Waste Dumps
- No Tailing Dumps
- No pollution of atmosphere
- Self-remediation of underground waters
Features of in-situ recovery deposits

- Location of mineralisation in or close to aquifer horizon(s)
- Permeable rocks
- Selective leachability of commodity of interest
- No adsorption minerals
- Low grades and high thickness are preferable
- Equally distributed and fine-grain mineralisation is preferable

Commodities amenable for In-Situ Recovery

<table>
<thead>
<tr>
<th>Lanthanide (REE)</th>
<th>Actinide (Act)</th>
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<tbody>
<tr>
<td>La</td>
<td>Ce</td>
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<tr>
<td>Act</td>
<td>Ac</td>
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</table>

- Uranium, ISR dominates
- Commodities, mined by ISR
- Commodities, successful field tests for ISR
- Commodities, successful laboratory tests for ISR
- Extraction as by-product in ISR
- Successful tests for extraction as by-products
- Potential mining by ISR
ISR historical overview in the non-uranium industry

Developing of in-situ recovery is more active than was predicted in 2015

Wide range of commodities and types of deposits are amenable for ISR now
Copper

- Arizona: San Manuel, Silver Belt, Miami (all depleted), Florence (operation), Gunnison (FS)
- Russia: Gumeshevskoye (operation)
- Zambia: Morani (operation)
- Kazakhstan: Kounrad waste (operation)
- Mongolia: Erdenet waste (operation)
- Australia: Moonta, Kapunda (all proposed)

ISR by sulphuric acid 5-20 g/l, extraction 30-90% Cu, pregnant solutions 0.5 – 1.2 g/l (3-5 US$/m³). Processing by solvent extraction and subsequently producing cathode copper 99.99%. OPEX is 2.0-2.5 US$/kg Cu
Gold and Silver

- Canada: tails on some mines (depleted)
- Russia: Gagarskoye, Dolgy Mys, Semenovskoye (all operation), Bystrinsko-Shirinsky, Tuba-Kain, Orlovskoye (FS, test operation)
- USA: Carlin type deposits in Nevada (proposed)
- Australia: Victorian Deep Leeds, Central Tanami (proposed)

ISR by Cl$_2$ or NaClO 0.3-1.2 g/l Cl, extraction 70-90% Au, pregnant solutions 0.1 – 0.5 mg/l (4-20 US$/m$^3$). Processing by sorption to resin and subsequently smelting. OPEX is 250-400 US$ / oz Au
Nickel and Cobalt

- Russia: Tochilnogorskoye, Kungurskoye, Rogozhinskoye (tests)
- Kazakhstan: Ekibastuz-Shiderty (test, Scoping), Shevchenkovskoye, Gornostaevskoye, Bugetkol (all proposed)

ISR by sulphurous acid 20 g/l, pregnant solutions 200-500 mg/l Ni and 10-20 mg/l Co (3-7 US$/m³). Extraction 50-80% Ni, 70-95% Co. Processing by sorption to resin, subsequent processing of eluate by neutralisation and series of liquid extraction processes, producing sulphates of Ni and Co. OPEX is 4.0-5.5 US$ / kg Ni
Scandium

Mining as by-product from uranium solutions:
- Russia: Dalmatovskoye – Dalur (operation),
- Kazakhstan & Uzbekistan – tests on various deposits

Extraction as by-product from uranium pregnant solutions, 0.2-0.8 mg/l Ni.
Sorption and producing ScF₃, Sc₂O₃, Sc-Al alloy

Potential mining as by-product from Ni-Co pregnant solutions:
- Kazakhstan – test on Ekibastuz-Shiderty deposit.
Manganese, Tungsten, Zinc

Manganese. Oxidised weathering crust. Klevakinskoye (Russia). ISR laboratory tests by sulphurous acid 5 g/l, extraction 95% Mn, pregnant solutions 25-30 g/l (40 US$/m$^3$). Direct electrowinning, producing MnO$_2$

Tungsten. Scheelite bearing weathering crust upon skarns in Kazakhstan. ISR field test by hydrochloric (27 g/l) and ethanedioic (14 g/l) acids. W in pregnant solutions 280 mg/l

Zinc. VMS fractured deposit. ISR laboratory tests by H$_2$SO$_4$ 5-10 g/l + NaCl 50 g/l in Amurskoye and Komsomolskoye deposits (Russia). Extraction 50% Zn.
Lead, PGE, Lithium, Boron

Lead. Carbonate-Sulphate mineralisation. Tests by Methanesulfonic acid (CH$_3$SO$_3$H) in Australia. Extraction 70-80%

PGE. ISR laboratory tests by NH$_4$SCN (5 g/l) + FeCl$_3$ in Russia. Extraction Pt 50%, Pd 70-80%

Lithium. ISR laboratory and field tests on the Falchani tuff deposit (Peru) and Fort Cady deposit (USA) by heated H$_2$SO$_4$ or HCl heated. Extraction 80-90%.

Boric acid. ISR field test on the Fort Cady deposit (USA) by heated HCl by push-pull method. Extraction up to 70%
By-product Se, Re, V, REE, Y, Mo

Selenium and Rhenium. Selenium and Rhenium are by-product components in uranium pregnant solutions: in Kazakhstan, Uzbekistan (sulphuric acid) and USA (bicarbonate and carbonate with oxidant).

Se grades 100-500 mg/l, recovery up to 35%. Re grades 0.2-0.8 mg/l, recovery up to 20%.

Rare Earth, Yttrium, Vanadium, Molybdenum are by-product components in uranium pregnant solutions in acid ISR (Russia, Kazakhstan, Uzbekistan). REE & Y grades are 15-30 mg/l, V 500 mg/l, Mo 250 mg/l.
Bio-oxidation of sulphide mineralisation

One of the most effective approaches is using Fe(III) as an oxidant by regeneration of Fe(II) to Fe(III) by oxygen of natural air in bioreactors.

This is recommended for oxidisation of copper sulphides such as chalcopyrite.

Scheme of ISR including two bio-technology options: (i) on-surface bio-oxidation of Fe in a bioreactor and (ii) stimulated in-situ bioleaching by oxidant injection

Source: Richter et al., 2018
In-Situ Recovery process is required some more detail investigations than for conventional mining:

- Full lithological model
- Detail hydrogeology
- Permeability
- Leachability of commodities
<table>
<thead>
<tr>
<th>Stage</th>
<th>Minimal requirements</th>
<th>Recommended requirements</th>
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<tbody>
<tr>
<td>Scoping Study</td>
<td>Mineralogical investigations, collection of all hydrogeological parameters, laboratory leaching tests for different parameters, reagents and oxidants, laboratory extraction metals from pregnant solutions</td>
<td>Plus push-pull or two-wells in situ leaching test without processing of pregnant solutions. Hydrodynamic modelling</td>
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<tr>
<td>Prefeasibility Study</td>
<td>Push-pull or two-wells in situ leaching test, extraction metals from pregnant solutions in laboratory</td>
<td>Multi-wells in situ leaching test; extraction metals from pregnant solutions in a pilot plant</td>
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<tr>
<td>Feasibility Study</td>
<td>Multi-wells in situ leaching test with processing of pregnant solutions in a pilot plant</td>
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Full lithological model is required for correct modelling of In-Situ Recovery process. This model is used for preparation of:

- Permeability model
- Hydrogeological model
- Hydrodynamic model
- Geo-metallurgical model
- Operational (mining) model
Full lithological model

Lithological and mineralisation model for roll-front uranium deposit

Lithological model for nickel-cobalt laterite deposit

Mineralisation model for roll-front uranium deposit

Mineralisation model for nickel-cobalt laterite deposit
Hydrogeology

Hydrogeological investigations include the following investigations:

- Aquifer horizons / complexes
- Regime (pressure or non-pressure) of aquifer complexes
- Connections between aquifer complexes
- Faults, fissure zones
- Rivers, channels, intake wells
- Intake (recharge) and discharge of water
- Direction and speed of natural flow of water
- Chemical composition of water
- Hydrology conditions including anisotropy: transmissibility ($m^2$/day), permeability (m/day), porosity / cavernous of rocks
Hydrogeology

Hydrogeological model

Cluster pumping hydrogeological test

Investigation of natural flow direction and velocity
Permeability is the one of the most important parameter of In-Situ Recovery:

- Permeability is measured directly by hydrogeological tests
- Variability of permeability is measured by indirect methods such as electro-logging
- Special investigations are required to define the dependence between hydrological parameters and results of any indirect methods
- Method of nuclear magnetic logging (NMR) is the best for measurements of porosity and permeability of rocks
Permeability

Permeability measurements using electro logging

Electrical Resistivity (Ωm), Ohm*m

Filtration coefficient, m/day

Permeability model for roll-front uranium deposit

NMR logging (Al-Harbī et al., 2007)
Mineralogy and Laboratory tests

Investigation of the composition, morphology and distribution of minerals is very important in the preparation of a geometallurgical test program.

- Metals in different valence form are dissolved in different rates and extraction level.
- Optical and CamScan microscopy, microprobe and diffraction assays are used for mineralogical investigations.
- Agitation leaching tests are required for the determination of “maximal” levels of extraction.
- Oxidants or reducing reagents may be recommended for extraction improvement.
- Column Filtration Leaching Tests are the most common tests conducted for geometallurgical investigations.
- Laboratory tests usually demonstrate a more rapid rate of leaching than natural field tests.
Mineralogy and Laboratory tests

- **CamScan**
- **X-Ray Diffraction**
- **Optical microscopy**

**Filtration column tests**
- Boyle's vessel with leaching solutions
- Glass pipe to feed the solution and control flow rate
- Tube with mineralised rocks
- Flask for collecting pregnant solutions

**Dynamic of extraction**

**X-Ray Diffraction**

**Liquid to Solid ratio (L/S)**

**Recovery (%)**
The progression of an ISR project from laboratory to multi-well in situ leaching field tests is the most critical step

- Multi-well in situ leaching field tests validate the assumptions and predictions of any earlier work: geological, lithological, leaching, hydrodynamic.
- Hydrodynamic modelling supports cluster tests and allows prediction of hydrogeological parameters.
- Refinement of well field modelling is the usual outcome of the multi-well test work. Any unsuccessful tests must be investigated.
- Geometallurgical parameters defined by multi-wells in situ field tests are considered sufficiently reliable for Prefeasibility and Feasibility Studies.
Natural Field Test

Hydrodynamic model

Processing Pilot Plant

Raw results of Natural Field Test

Modelling of geo-metallurgical parameters using raw results

Uranium in pregnant solutions
Uranium extraction
H₂O₂ consumption kg/t
Acid consumption kg/t

Acidification
Flow rate
Leaching
U grade in barren solutions
Extraction U

Liquid to Solid ratio (L/S)

Liquid to Solid ratio (L/S)

Eh in injection wells
Fe⁺
Eh in production wells
Fe²⁺

Liquid to Solid ratio (L/S)