In situ recovery
Opportunities, challenges and solutions

Dr. Maxim Seredkin
Dr. Igor Solodov
In situ recovery (ISR) is one of the most effective methods to address the costs of mining. The key feature of ISR is transferring a significant proportion of hydrometallurgical processing to the subsurface to directly obtain solutions of the metals of interest.
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.
The main economic advantages of ISR include:

• Lower mine development costs, including processing plant and infrastructure, in comparison with conventional open pit and underground mines.

• Lower operating costs.

• The ability to commence production with low capital costs and subsequently increase production. Early cash flow from concentrate production is used to further develop the mine rather than using borrowed funds.

• Flexibility of production capacity. Production can be reduced during periods of lower prices and increased when prices are higher.
ISR may be able to be used for deposits which are not profitable using conventional mining methods.
ISR in comparison with conventional open pit and underground mines:

- Lower CAPEX
- Lower OPEX
Opportunities – Economics

- ISR gives ability to commence production with low capital costs and subsequently increase production. Early cash flow from concentrate production is used to further develop the mine.

- ISR gives flexibility with production. Production can be reduced during periods of lower prices and increased when prices are higher.
Opportunities – Environmental

Conventional mining

In situ recovery
The economics of ISR mines primarily depends on:

- Flow rate capacity of the wellfields (input capacity of injection wells and extraction capacity of production wells).
- The concentration of extracted component(s) in pregnant solutions.
- The overall level of extraction of the economic component(s).
- Ratio of Liquid to Solid (L:S) required to achieve the desired extraction.

Which issues may influence to effectiveness and profitability of in situ recovery mines?

How these issues may be resolved?

Industry has gained experience with these issues and developed solutions to address them.
Liquid to Solid ratio (L:S) is the best parameter to assess the economics of ISR projects, where “Liquid” is volume of leaching solutions and “Solid” is ore tonnage. L:S is function of time, flow rate capacity and leaching dynamics. The L:S value for optimum extraction is critical for ISR projects.
The dynamics of leaching in ISR deposits depends on grade-thickness more than grades. Lower grades with higher thicknesses are more favourable than higher grades with lower thickness.

Block A: $GT_U = 17.4 \text{ kg/m}^2$, $C_U = 0.048\%$
Block A: $GT_U = 14.0 \text{ kg/m}^2$, $C_U = 0.045\%$
Block A: $GT_U = 7.5 \text{ kg/m}^2$, $C_U = 0.044\%$
Hydrodynamic Issues

- Stagnant non or slow leaching zones
- Formation of “channels” – zones of predominant flow of leaching solutions
- Spreading of leaching and/or pregnant solutions outside operational blocks
- Dilution of pregnant solutions by surrounding underground water
- Dilution of pregnant solutions by rain/superficial water for superficial deposits
- Disbalance of injection of leaching solutions and pumping of pregnant solutions
- Change in the underground water level.
Changing the Hydrodynamic Regime

Hydrodynamic modelling, optimal design of operational blocks and changing the regime of wells from injection to pumping (or opposite) are the most typical solutions for freeing stagnant zones, decreasing spreading of solutions and avoiding the formation of “channels”. Calibration of the rate of injection and pumping in each well is also useful. These solutions may also lead to lower dilution of pregnant solutions by underground water.
Dilution of working solutions by rain water can be managed by isolation of surface blocks from rain water penetration.

Dilution of pregnant/leaching solutions by underground water or contamination of underground water by pregnant solutions may happen due to disruption of pipes in wells. This can be identified by logging of wells (induction, resistivity, monoelectrode electrical and flowmetry).
A higher rate of pumping (than rate of injection) of leaching solutions may lead to lowering the underground water level. This may lead to “losses” of Mineral Resources acceptable for ISR. The balance of injection and pumping rates should be monitored during ISR operations.
Issues with Installation of Filters

For ISR projects, lithological and mineralisation modelling is critical for the correct planning of operational block configuration as well as screen (filter) positioning and installation. Poor modelling of lithology can lead to incorrect installation of filters.
Very long filters (> 8 to 10 m) don’t work correctly. Solutions don’t flow through parts of the filters, therefore upper parts of the mineralised body cannot be leached. In this case, 2 or more levels of operational blocks are strongly recommended.
Issues with Installation of Filters

Detail investigation of geological features is critical for designing operational blocks for ISR mines in weathering crust where a combined method is used for leaching:

- 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
- Conventional ISR (filtration) below the water table.

The disintegration zone in the bottom layer of the weathering crust is the most suitable for collection of pregnant solutions.
The distribution and style of mineralisation — the location and exposure of target mineral grains — strongly affects leachability. Oxidized or reduced target component(s) as well as the composition of host rocks influence composition of leaching solutions. Lixiviants are not enough for leaching of reduced minerals, oxidants must be used for transformation minerals to leachable forms.
Fe(III) in leaching solutions is a universal oxidant and it may be produced in solutions in different ways, by using different oxidants such as hydrogene peroxide and sodium nitrite.

Examples of oxidation reactions:

**Uranium**

Fe$^{2+}$ (silicate iron) + H$_2$O$_{pp}$ \( \rightarrow \) [Fe$^{3+}$(OH)$_2$]$^+_{pp}$

FeS$_2$ (pyrite) + H$_2$O$_{pp}$ + 4H$_2$O \( \rightarrow \) [Fe$^{3+}$(OH)$_2$]$^+_{pp}$ + 2H$_2$SO$_4_{pp}$

Fe$^{2+}$ (silicate iron) + FeS$_2$ (pyrite) + 16NaN$^3$O$_2$ + 6H$_2$SO$_4 \rightarrow$ 2[Fe$^{3+}$(OH)$_2$]$^+_{pp}$ + 16N$^{2+}$O + 8Na$_2$SO$_4$ + 4H$_2$O

U$^{4+}$O$_2$ (uraninite) + 2[Fe$^{3+}$(OH)$_2$]$^+_{pp}$ \( \rightarrow \) [U$^{6+}$O$_2$]$^{2-}_{pp}$ + 2Fe$^{2+}$(OH)$_2_{pp}$

[U$^{6+}$O$_2$]$^{2-}_{pp}$ + H$_2$SO$_4_{pp} \rightarrow$ U$^{6+}$O$_2$SO$_4_{pp}$ + H$_2$O

**Copper**

Fe$^{2+}$ (silicate iron) + H$_2$O$_{pp}$ \( \rightarrow \) [Fe$^{3+}$(OH)$_2$]$^+_{pp}$

Cu$^{2+}$Fe$^{2+}$S$^{2-}_{2}$ (chalcopyrite) + 16[Fe$^{3+}$(OH)$_2$]$^+_{pp} \rightarrow$ Cu$^{2+}$S$^{6+}$O$_4_{pp}$ + Fe$^{2+}$S$^{6+}$O$_4_{pp}$ + 8Fe$^{2+}_{pp}$ + 8Fe$^{2+}$(OH)$_2_{pp}$ + 8H$_2$O

Cu$^{+}_{2}$S$^{2-}$ (chalcolite) + H$_2$S$^{6+}$O$_4_{pp}$ + 10[Fe$^{3+}$(OH)$_2$]$^+_{pp} \rightarrow$ 2Cu$^{2+}$S$^{6+}$O$_4_{pp}$ + 5Fe$^{2+}_{pp}$ + 5Fe$^{2+}$(OH)$_2_{pp}$ + 6H$_2$O
Oxidants allow increased leaching and extraction levels of useful components. This is caused by increasing the leaching of minerals due to transformation to leachable forms: U⁴⁺ to U⁶⁺, copper sulphides to sulphates and others. Also some host minerals which cover the useful minerals, may be destroyed easily by oxidants.
Issues with Mineralogical Composition

One of the most effective ways is using Fe(III) as an oxidant by regeneration of Fe(II) to Fe(III) by oxygen of natural air in bioreactors. This way was 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.
Issues with Mineralogical Composition

In some situations, common reagents cannot be used due to environmental requirements or non-selective leaching of useful minerals. Uncommon reagents are often unstable and must be produced on site.

\[ \text{NaCl}_{p} + \text{H}_2\text{O} + \text{electrical discharge} \rightarrow \text{NaClO}_{p} + \text{H}_2 \]

\[ 2\text{Au} \text{ (natural)} + 3\text{NaClO}_{p} + 5\text{NaCl}_{p} + 3\text{H}_2\text{O} \rightarrow 2\text{Na[Au}^{3+}\text{Cl}_3]_{p} + 6\text{NaOH}_{p} \]

Cyanides cannot be used for ISR of gold. Sodium hypochlorite is alternative lixiviant for gold leaching. It may be produced on site from rock salt. Gold in copper-gold deposits should be leached by thiourea after copper leaching by acid.

\[ \text{S} + \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_3 \]

\[ \text{Ni}^{2+} \text{ (silicate)} + \text{H}_2\text{SO}_3 \rightarrow \text{NiSO}_4 + \text{H}_2 \]

Leaching of nickel-bearing saprolites and laterites by sulphuric acid leads to the dissolution of both nickel mineralisation and rock-forming minerals with enrichment of pregnant solutions in iron and silica. Sulphurous acid is used for selective leaching of nickel and cobalt. This method is effective despite lower grades of nickel in pregnant solutions (80–120 mg/l vs 1–4 g/l) and weak dynamics of leaching.
Issues with Host Rocks

Host minerals are exposed to lixiviant and oxidants with full or partial congruent or incongruent dissolution. This is one cause of chemical colmatage (incrustation) of the mineralised horizon, filters and wells. Dissolution of some minerals (for example, carbonates) leads to gas colmatage (blockage) of mineralised horizons.
Solutions adopted for avoiding issues with colmatage include:

- Devising a special procedure for acidification, with a gradual increase in acid (or any reagent) concentration for control of kinetic of chemical reactions such as dissolution of carbonates or sulphides.
- Repair-recovery works for wells when blockage occurs.
Issues with Host Rocks

Colmatage of filters is also caused by fine particulates which are often moved due to the flow of working solutions.

Construction of operational wells including using special filters (screens), forming of a special gravel zone surrounding screens, and preparing cement rings above and below screen are solutions.
Cleaning solutions by removal of fine solid material in special ponds and/or fabric is the conventional approach for ISR mines.
In a properly designed wellfield, the extent of the halo of leachant is limited by hydrodynamic balance within the wellfield. Groundwater contamination takes place within a zone of <100 m of hydraulic influence near leaching wells, and does not move along the stratum. Monitoring wells around ISR polygons allows control of conditions within the aquifer.

Another environmental risk is surface contamination and damage to soils. Contamination during an ISR operation should be minimal with good environmental control.
The hydrogeology returns to the natural flow of groundwater after depletion of ISR blocks. Many studies have shown that the geological substrate leads to self-cleaning of solutions due to reactions between solutions and host rocks as well as bacterial activity. However, decisions regarding the requirement to clean an aquifer should be taken based on studies and on the availability of water intakes. Cleaning 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.

1 – halos of sulphate ions during ISR operation, 2 – neutralization barrier, 3 – reducing barrier, 4 – natural flow of underground water, 5,6 – observation holes, 7 – operational wells, 8 – resources.
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