A new mining concept for extraction of metals from deep ore deposits using biotechnology

D7.1

Economic evaluation of coupled chemical-biochemical underground block leaching scenarios
Umwelt- und Ingenieurtechnik GmbH Dresden

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EUROPEAN UNION
This project is funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No 642456.
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<th>Item</th>
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<tr>
<td>D7.1 Economic evaluation of coupled chemical-biochemical underground block-leaching scenarios</td>
<td></td>
</tr>
<tr>
<td>Due date of Deliverable</td>
<td>2018-07-31</td>
</tr>
<tr>
<td>Actual Submission Date</td>
<td>2018-07-31</td>
</tr>
<tr>
<td>Start Date of Project</td>
<td>2015-02-01</td>
</tr>
<tr>
<td>Duration</td>
<td>42 months</td>
</tr>
<tr>
<td>Deliverable Lead Contractor</td>
<td>UIT</td>
</tr>
<tr>
<td>Revision</td>
<td>Version 1.0</td>
</tr>
<tr>
<td>Last Modifications</td>
<td>2018-07-30</td>
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<tr>
<td>Nature</td>
<td>R</td>
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<tr>
<td>Dissemination level</td>
<td>PU</td>
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<tr>
<td>Public Summary enclosed</td>
<td>no</td>
</tr>
<tr>
<td>Reference / Workpackage</td>
<td>WP7</td>
</tr>
<tr>
<td>Digital File Name</td>
<td>De-180831-0051 - D7.1 Economic evaluation of coupled chemical-biochemical underground block-leaching scenarios</td>
</tr>
<tr>
<td>Document reference number</td>
<td>De-180831-0051</td>
</tr>
<tr>
<td>No of pages</td>
<td>94 (incl. cover and annexes)</td>
</tr>
<tr>
<td>Keywords</td>
<td></td>
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<tr>
<td>In bibliography, this report should be cited as follows:</td>
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<tr>
<td>a</td>
<td>Annum (year)</td>
</tr>
<tr>
<td>AEC</td>
<td>Anion Exchange Capacity (e.g. of clays, IX resins.)</td>
</tr>
<tr>
<td>BPT</td>
<td>Best Practice/Practicable Technology</td>
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<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>CEC</td>
<td>Cation Exchange Capacity (e.g. of clays, IX resins.)</td>
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<tr>
<td>CLC</td>
<td>Cobre Las Cruces, S.A. (Spain). Mining company. Partner in BIOMOre.</td>
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<tr>
<td>CNRS</td>
<td>Centre National de la Recherche Scientifique (National Center for Scientific Research), France, Partner in BIOMOre.</td>
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<tr>
<td>d</td>
<td>Day</td>
</tr>
<tr>
<td>D</td>
<td>Darcy (old unit of hydraulic conductivity/permeability)</td>
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<tr>
<td>EC</td>
<td>Electroconductivity, usually measured in mS/cm or µS/cm (S – Siemens)</td>
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<tr>
<td>Eh</td>
<td>Redox potential (of a solution) with reference to the hydrogen electrode. Cf. ORP</td>
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<tr>
<td>EIA(EIS)</td>
<td>Environmental Impact Assessment (Statement)</td>
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<tr>
<td>EPS</td>
<td>Extracellular Polymeric Substance</td>
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<tr>
<td>ENA</td>
<td>Enhanced Natural Attenuation</td>
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<tr>
<td>ETW</td>
<td>Effluent Treatment Plant</td>
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<tr>
<td>EW</td>
<td>Electrowinning</td>
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<tr>
<td>FEFLOW</td>
<td>(Software) Finite Element subsurface FLOW system. Computer program for simulating groundwater flow, mass transfer and heat transfer in porous media and fractured media</td>
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<tr>
<td>FIGB</td>
<td>Ferric Iron Generating Bioreactor</td>
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<tr>
<td>FLT</td>
<td>Field Leach Trial</td>
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<tr>
<td>GEIS</td>
<td>General Environmental Impact Statement</td>
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<tr>
<td>GT</td>
<td>Grade x Thickness [wt%·m], cf. Productivity (Glossary)</td>
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<tr>
<td>GW</td>
<td>Groundwater</td>
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<tr>
<td>h</td>
<td>Hour</td>
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<tr>
<td>HF</td>
<td>Here: Hydraulic Fracturing.</td>
</tr>
<tr>
<td>HRT</td>
<td>Hydraulic Retention Time</td>
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IMN (Instytut Metali Nieżelaznycych) Institute of Non-Ferrous Metals, Gliwice, Poland
ISF Imperial Smelting Furnace
ISL In-Situ Leach(ing), also referred to as In-situ Recovery ISR
ISR In-Situ Recovery, also referred to as In-situ Leach(ing) ISL
IX Ion eXchange
kg Kilogramm
KGHM (Former Kombinat Górniczo-Hutniczy Miedź). Polish Mining Company (nowadays KGHM Polska Miedź SA) and partner in the BIOMOre project.
KiLea-Hy (Generic) Kinetic Leach Model Software for ISR feasibility studies and the prediction of ISR production rates in dependence on deposit parameters and wellfield design. Extended to block leach applications within the BIOMOre project, i.e. extended to various Hydrological scenarios.
km Kilometer
kWh Kilowatt hour
L (or l) Liter
LME London Metal Exchange
LSR (sometimes L/S or S/L) Liquid to solid ratio (e.g. leachant mass per ore mass in leaching operations)
m Meter
M Mole (mM – millimole)
MARP Mining And Rehabilitation Program
METSIM (Software) Steady-State & Dynamic Process Simulator for chemical and metallurgical processing
mg/L Milligrams per liter (also referred to as ppm – parts per million)
MNA Monitored Natural Attenuation
NA Natural Attenuation
NF Nanofiltration
NPV Net Present Value (model for economic assessment)
OPEX Operational Expenditure
ORP Oxidation-Reduction Potential (as measured with reference to dedicated electrodes). Cf. Eₜₜ.
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Executive summary

This report summarizes the results of the first part of the prefeasibility study, economic assessment and pilot preparation, in particular, focusing on the “economic evaluation of coupled chemical-biochemical underground block-leaching scenarios (sandstone, shale, carbonate) in a ca. 100 m³ in-situ ore block at a KGHM Cu mine test site in Poland, including biochemical, hydrogeological (e.g. effective permeability) and metallurgical assessment (e.g. leaching efficiency, pH, acid/oxidation ratios) with options for optimization of the leaching scenarios.” (General Agreement, BIOMOre).

Since the block leaching has been considered as a special application case of in-situ recovery (ISR) accessible to the BIOMOre consortium (i.e. performing ISR in underground mineworks), the actual industrial standard of wellfield based ISR from the surface is outlined and characterized. The wellfield based ISR is considered to be the preferred potential application case for any pilot action. ISR has been categorized in the overall recovery and processing scheme of metals including pyrometallurgical and hydrometallurgical processing. Whereas bioleaching in tanks and heaps has already been successfully implemented in the industry for many years (applying various specific technologies supported by aeration for providing the oxidant for leaching metals from reduced minerals), (quantitative) bioleaching in real ISR applications is still not fully understood, but attracts increasing interest worldwide. Its industrial-scale use is pending. Whereas the actual in-situ bioleaching requires the quantitative availability of an oxidant (O₂ dissolved in the leachant), the alternative on-surface biooxidation of Fe²⁺ to Fe³⁺ in the leaching solution has been primarily investigated in the BIOMOre project.

In order to relate ISR as a (in general) very economic mining option within the current trend of industry 4.0 development, the specific requirements for applying ISR 4.0 (defined in the context of the historic development of ISR technology before) are summarized. There is a significant potential to optimize ISR by applying various digitized-world technologies including advanced geophysical assays, 3D modelling of the hydrogeological framework (orebody, 3D deposit conditions determining the leaching rates), model-based expert systems to follow-up the in-situ depletion of the metal of interest by reactive-transport simulations in 3D, advanced capabilities for the design and engineering of processing plants, model-based expert systems to optimize the metallurgical processing, automation of operation, monitoring, and environmental management etc.

This report describes the main principles of ISR (industrial, wellfield-based operation) in detail and generalizes the feasibility criteria as basis for the further assessment:

- The hydrogeological criteria (porosity, permeability, and confinement predominantly) together with the orebody morphology (including ore grade distribution) define the achievable volumetric flow and, hence, the determining pore volume exchange (PVE) rate. The optional wellfield stimulation by fracturing could enhance the permeability for increasing recovery.
• The mineralogical/geochemical, groundwater-chemical and microbial criteria define the leaching kinetics, usually expressed by absolute kinetic rates as function of chemical and optionally microbial parameters. Pre-conditioning could improve/expedite the recovery for a more economic operation.

• Both, flow rate of leaching solution and metal grade in the pregnant leach solution (PLS) determine the production rate as the basis for the economic assessment of the ISR technology. It is combined with the (in general, hydrometallurgical) processing (either ion-exchange IX or solvent extraction SX to separate the metal of interest from the PLS, in each case followed by electrowinning EW or alternative separation/refining technologies.

The applicability of permeability stimulation technologies has been briefly reviewed. It is dependent on geomechanical deposit characteristics. The options include hydraulic fracturing (up to 100 MPa pressure), acidizing (to dissolve minerals and open pathways), thermal fracturing (cold-water injection), and other techniques (like explosives, acoustic methods, electric stimulation). Due to the incompressibility of rock, the effect on porosity enhancement is marginal; however, the above technologies are suitable to improve hydraulic pathways by creating cracks/fractures and connect isolated pores to contribute to the fluid flow. The effect is in the order of several tenth %, thus, resulting in a significant increase of the productivity of wells in the oil & gas industry. The Rudna test, however, where the above methods were not applicable for various reasons (physical through permitting conditions), the classical drilling & blasting technology has been applied including the creation of a compensation volume (WP3).

The potential role of microorganisms in the in-situ recovery (ISR) of technology metals, in particular from reduced ores, is not fully understood, but attracts increasing interest worldwide. Based on the feasibility criteria for ISR applications in general, effects of biota on kinetic rates of leaching are systematized. The indirect catalysis of leaching by microbial (re-)oxidation of Fe$^{2+}$ to Fe$^{3+}$ as directly acting e- acceptor is a well verified mechanism, however, for practical applications this requires the availability of an oxidant in the leachant. The ex-situ bio-oxidation of Fe in an aerated bioreactor is considered as an alternative. Reactive transport simulations of ISR from sulfidic Cu ores based on kinetic rates as function of pH and oxidation potential (concentration of e- acceptors) in comparison with thermodynamically driven metal dissolution (constrained by oxidation potential) demonstrate the key parameters for (bio-)leaching productivity (Richter, Kalka, & Märten, 2017).

A generic kinetic leach model (KiLea-Hy) has been developed that enables the fast simulation of production rates (flow rate x metal concentration) during the lifetime of an ISR operation including (i) the (standard) wellfield operation and (ii) the specific block leaching in underground mineworks. KiLea-Hy has been setup for the leaching of U (as industrial reference case for validation), for Cu (the target element within the BIOMOre project) and Zn so far. Extensions to other metals are easily possible. The acid leaching of metals from reduced (sulfidic) ores has been implemented as a standard, however, alkaline leaching is also considered for U. The ISR hydrology is simulated on the basis of empirical relations that were deduced from 3D hydrological modelling of wellfield and block leaching in situ. Several simulations are reported in order
to quantify the dependence of production rates on deposit conditions. The most critical ones for the ISR of metals from reduced ores include:

- Influence of porosity/permeability (both are interrelated) on PVE rate and production rate finally. Definition of approximate threshold values for
  - A technically feasible operation (conditions to realize a viable operation)
  - An economic recovery (considerably determined by the market price of the metal of interest.

The actual threshold values for both, porosity $\varepsilon$ and permeability $\kappa$, depend on deposit conditions and, last not least, on market price of the commodity. In most cases, $\varepsilon > 12\%$ and $\kappa > 0.1$ m/d (ca. 120 mD) apply – for low-value metals higher. This ISR feasibility window might be different for very coarse-grained sediments or very silty/clayey sediments.

- Importance of oxidant concentration, either in form of ferric iron $\text{Fe}^{3+}$ as electron acceptor (direct oxidation of minerals) or in form of dissolved $\text{O}_2$ (for the indirect bioleaching). Limited availability of oxidation potential might result in (thermo-dynamic) leaching constraints, thus, reducing the productivity accordingly. The effect of oxidant concentration on productivity is mainly determined by the number of electrons exchanged for the oxidation of the relevant mineral containing the metal of interest (i.e. the redox charge balance).

- Impact of competing minerals consuming reactants and constraining the leaching rate of the metal of interest:
  - Neutralizing minerals (e.g. calcareous minerals consuming sulfuric acid),
  - Reduced minerals (e.g. pyrite) consuming oxidation potential and organics undergoing oxidative degradation under acidic conditions.

An abundance of calcareous minerals in the order of 1 wt% becomes already critical, in particular due to the risk of quantitative gypsum precipitation under sulfuric acid leach conditions (thus, plugging well screens and formation pores and reducing flow rates down to vanishing). At abundances in excess of 2 wt%, the acid ISR is no longer feasible. The impact of competitive sulfidic minerals and organics has to be assessed for the specific site, since several factors (mineral texture and specific kinetic rates as function of leaching chemistry) have to be taken into account.

- Potential of wellfield design (hydrological) and wellfield performance (chemical) on productivity in general. This is the most important role of ISR know-how and engineering.

The software KiLea-Hy is suitable to reproduce the block leaching test results obtained from the Rudna mine test and, most important, to convert the test results into the recovery functions for the corresponding wellfield ISR case consistently.

The generic pre-feasibility study for the ISR option described in this report (i.e. generalizing/quantifying the productivity of ISR in dependence on both, realized flow rate
and leaching rate, both determining the production rate finally) provides the input for the economic assessment described in deliverable D7.2 (there combined with the subsequent hydrometallurgical processing) and the complete economic assessment of an ISR project by applying a NPV (net present value) model (combining CAPEX/OPEX and other expenditures with estimated revenue figures throughout the lifetime of the mining project.
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1. Scope of work and general approach

1.1. Scope of work of WP7 and links to other BIOMOre work packages

In the BIOMOre project, in-situ leaching in combination with biotechnology as a more valuable mining method is conceptually studied, lab-scale-tested (WP1), simulated by modelling (hydrological/reactive-transport) (WP2), trialled by setting up a leach block underground and running a pilot plant at KGHM’s Rudna copper mine (Poland) (WP3), and finally assessed in the context of technological and environmental conditions (WP4 and WP5). The main objective of this project is to develop and evaluate an alternative mining technology and to define the conditions for the economic application of in-situ leaching, in particular, in application cases where conventional mining is no longer economic. These include low-grade ores and/or deposits at high depth.

The role of WP7 in the BIOMOre project is illustrated in some detail in Figure 1.

**Figure 1: Role of WP7.**

The corresponding workflow (interaction and interfaces) realized during the BIOMOre project is shown in Figure 2.

WP1 includes the lab-scale testing of the leaching and biotechnological aspects to demonstrate the feasibility and quantify process parameters provisionally. Reactive-transport modelling (in detail developed and applied in WP2) combines all determining factors, most important pore volume exchange rate (PVE) and metal leaching rate and is used to predict recovery curves. PVE rates are usually deduced from (2D-3D) hydrological modelling as the basis for the well field design. The detailed model results from WP2 together with experimentally determined parameters (WP1, WP3) were used for applying the kinetic leach model KiLea-Hy (1D reactive transport) for the estimation of recovery curves dependent on deposit parameters (most important:
porosity, permeability, kinetic rates of target metal and interfering minerals as function of chemical conditions, also considering microbial effects, i.e. bioleaching, as far as reliable input parameters are available) and well field design/ISR performance (most important: flow and PVE rate, leachant chemistry, recovery efficiency). The model results are directly coupled to an economic model for estimating specific OPEX in WP7, Task 7.2 (energy costs for pumping, chemicals’ consumption costs, etc.) together with estimates of CAPEX for the ISR facility including wellfields. In addition, Task 7.2 evaluates the CAPEX/OPEX for the subsequent hydrometallurgical processing for metal production on the basis of WP4.

Interaction and interfaces with other WP's

WP1
Test data/parameters/mass balance/recovery. Input to integrative economic model.

WP2
Results from simulations (together with input/scenarios/uncertainties) for integrative economic model.

WP3
Test data. Cost factors in test scale. Input parameters for integrative economic model.

WP4
Design, mass balance. CAPEX/OPEX figures for integrative economic model.

WP5
Scope of environmental measures and mine-closure - cost figures for integrative economic model.

WP6
Applicable conditions: (i) regulatory requirements, (ii) public acceptance, (iii) economic/market framework, ...

Compilation, analysis, evaluation of CAPEX/OPEX vs. value of metal recovery as function of leaching efficiency and hydrogeological/biochemical leaching scenarios. [Integrative process simulation + economic model]

Assessment/optimization of entire Cu recovery comprising (bio-)leaching and Cu recovery/processing for maximum cost/yield efficiency and profitability.

Comparison of predicted Cu recovery costs (Including uncertainty/risk aspects) within Cu mining industry.

Figure 2: Schematic of WP7 workflow.

As underground block leaching is a rarely applicable and a very special case, the studies in WP7 focus on standard in-situ recovery (wellfield operation from the surface) in general. The scope of assessment within WP7 is schematically shown in Figure 3 (highlighting the cycle from WP7.1 to WP7.4).
1.2. Classification of ISR within conventional mining and metallurgical processing

Figure 4 illustrates the pyrometallurgical processing chain for a complete overview only. The run of mine (ROM) ore is comminuted (crushed/ground), concentrated by physical processing (including flotation and other methods), and smelting and electro-refining results in the pure metal product.

Chemical digestion (also referred to as leaching) is the basic hydrometallurgical processing step, resulting in a pregnant leach solution (PLS). The metal of interest is recovered from the PLS by selective technologies including ion exchange (IX) and solvent extraction (SX), then applying electrowinning or alternative methods (e.g. selective precipitation) to produce the pure metal.

The bioleaching is successfully applied in tank and heap leaching applications where the O₂ as oxidant is easily (and cost-effective) available by aeration. What specific methods are applicable to apply bioleaching in ISR applications? BIOMOre considers the ex-situ biooxidation of Fe (to generate ferric iron Fe³⁺ as a direct oxidant). The potential role of additional in-situ bioleaching effects is also addressed in WP7.
Deliverable D7.1 outlines the method of ISR itself, i.e. how to get the metal of interest into the PLS by applying wellfield system, and defines the methodology to quantify the production rates for given deposit conditions and wellfield design. Deliverable D7.2 investigates CAPEX and OPEX figures for both the primary ISR (from “ore” to “metal in solution”) and the subsequent processing to produce the pure metal.

1.3. Current ISR trend – towards ISR 4.0

As an overall trend, the potential of industry 4.0 is increasingly applied to conventional mining operations.

Figure 5 summarizes the ISR development trends in the uranium mining sector. At present, more than 50 % of the uranium worldwide is produced by ISR technology (trend increasing). It turned out to be the most economic mining technology under the quite recessive market conditions of the past years.

Within WP7, the economic assessment of alternative ISR applied to other than U minerals is considering the long-term experience from uranium ISR operations, i.e. using tools and main experience from there. BIOMORE contributed to the development of preconditions towards the application of ISR 4.0 solutions to other metals. Most prospective candidates have been investigated in WP7, Task7.4.

An overview of state-of-the-art methods used in ISR (with trends towards ISR 4.0) is given by Märten et al., 2015.
Figure 5: Overview on ISR development trends and brief characterization of ISR 4.0 (referring to the uranium ISR industry mainly, but ISR 4.0 applies to other metals in particular).
2. ISR – Characterization of the Industrial Standard

2.1. General characterization of ISR and main applications

In contrast to conventional mining methods including underground mining and open pit operations, i.e. based on the recovery of the ROM ore for further metallurgical processing (comminution and optionally physical beneficiation, either pyrometallurgical or hydrometallurgical technology), ISR is applicable to sedimentary-hosted deposits in confined aquifers at sufficient hydraulic permeability and appropriate mineralogy/geochemistry suitable to leach the metal of interest quantitatively. Essentially, ISR is the operation of wellfields by continuously recycling the leaching solution (‘lixiviant’) after metal capture (usually by ion exchange or solvent extraction) and subsequent refortification (chemical conditioning) before re-injection.

In exceptional cases, ISR has been applied to ore blocks in underground mineworks, also referred to as block or stope leaching, and leaching of (blasted) sidewalls of open pits (O’Gorman et al., 2004). A comprehensive review of block leaching methods has been documented under WP7.2 of this project (UIT, 2016), and was handed over to WP3 for consideration in setting up the block leach trial.

Most applications of ISR focus on uranium and oxidic copper ores, but sulfur, salt, brine, potash, phosphate, nickel, zinc, and gold can also be leached (O’Gorman, Von Michaelis, & Olson, 2004). ISR of uranium from sandstone type deposits was developed in the early 1960s (Lambert, 2010).

In 2011, about 45 % of uranium in the world was produced by ISR (Gallegos, Bern, Birdwell, Haines, & Engle, 2015), meanwhile exceeding 50 %. This method demonstrated lower cost uranium production, e.g. in Wyoming, Texas, Eastern Europe, Kazakhstan, and Russia, compared to conventional mining (underground, open pit) and processing. Due to the lower costs, ISR can also be applied economically at low grade ores.

Copper is successfully leached on sites in Arizona and in Zambia (see deliverable D5.3), but copper recoveries are often low (in the order of 20 to 25%). Nonetheless, it is believed to be economically viable (O’Gorman et al., 2004). An overview of copper ISR operations is given in Table 2 in deliverable D5.3.
2.2. ISR – well field operation

2.2.1. General ISR process

ISR is usually performed by setting up a well field of vertical injection and extraction wells with filter sections covering the ore body horizon. The leaching solution is injected through injection wells into the ore body (leaching zone) where the leachant dissolves the metal of interest.

The metal bearing solution (pregnant leach solution PLS) is pumped to the surface through extraction wells. The PLS is processed to recover the metal and the barren solution is readjusted (refortified) by the controlled dosage of chemicals and re-injected into the leaching zone. Figure 6 illustrates the ISR process in detail. Major characteristics include:

- Injection and extraction wells form a pattern with screened (filter) sections in the ore horizon. Spacing between wells is adjusted to deposit conditions. Depending on individual design criteria, the ratio of the number of injectors and extractors is usually in the order of 2. A sufficient groundwater head is required for operating the extraction pumps productively. The extraction wells are equipped with pumps close to the screen sections.

- So-called wellhouses distribute the injection solution to the injection wells at carefully controlled injection pressure/flow rate. On the other side, the PLS streams from the extraction wells are collected and pumped to the processing plant (in some cases satellite operations). Extraction filters are used to remove solid/suspended matter that might be mobilized as a side effect of leaching (e.g. mobilized clay fines, biomass).

- The metal of interest is recovered (removed) out of the PLS by IX or SX resulting in a barren solution that is refortified (chemically adjusted or conditioned/refortified) before re-injection. Booster pumps generate the required pressure for lixiviant transport through trunklines and injection.

- The main operational expenditures for ISR are symbolized in Figure 6, mainly including energy consumption for pumps (E) and dosage of chemicals (C).

- ISR wellfields are developed consecutively in a balanced manner to realize a nearly constant production throughout the lifetime of the project. On the other side, depleted wellfields are shutdown (typically by consecutively turning-off extractors with reference to the cut-off lix grade that is determined by ISR economics).

- The wellfield hydrology needs to be balanced with regard to pressure conditions and flow rate carefully in order to avoid unwanted migration/excursion of the lixiviant into the environment.

- Flow rate balance is controlled more reliably by applying a so-called bleed, i.e. the extraction flow rate is higher than the injection flow rate by about 0.5 % (up to 5 % in exceptional cases).
Figure 6: General scheme of ISR.
Wellfield monitoring is performed with regard to:

- Pressures and flow rates (as discussed above), usually assessed with reference to hydrological wellfield simulation (2D-3D).
- Water quality at the periphery of the wellfields (often including neighbour formations/strata) to identify unwanted lixiviant migration (Davis & Curtis, 2007).
- Lixiviant parameters (to follow up the chemical conditions/composition, in particular, comparing injection and extraction chemistry with reference to reactive-transport models).

In addition to environmental compliance, the main objective of monitoring the operational (hydrological, chemical) conditions of ISR is to control the wellfield operation and to optimize the performance with reference to hydrological/reactive-transport models.

Based on wellfield monitoring the operator is able to identify less than expected recovery and to conclude about adjustments of wellfields including role reversals (extractor<->injector), re-screening (adjust filter intervals), construction of additional in-fill wells, etc.

### 2.2.2. Feasibility criteria for ISR application

Determining deposit criteria for an ISR operation include (Mudd, 1998; Sarangi & Beri, 2000):

- Orebody hosted in porous, permeable rocks (usually sandstone formations).
- Confined above and below by continuous impermeable strata such as clays or shales (confinement condition).
- Located in a geological formation with no or tolerable irregularities, such as tectonic faults (potential migration of leaching solution).
- Located well below the groundwater table and therefore saturated with naturally occurring groundwater (hydraulic head condition for extraction wells).
- Suitable mineral matrix of the orebody, i.e. leachable metal mineral occurrence and small to tolerable abundances of interfering minerals.
- Small to tolerable heterogeneities with regard to hydrological and mineral/geochemical conditions.

Wellfield design and performance concept comprises the two essential sides of an efficient ISR operation (cf. Figure 7):

- Part I - ISR hydrology:
  Establishing the optimum contact (interface) of the lixiviant to the ore (microscopically to the metal-bearing mineral).
Optionally, the hydrological conditions for ISR could be improved by permeability enhancement techniques like fracturing. The preconditions and achievable effects will be discussed below.

- Part II - ISR (bio-)chemistry:
  Setup of the most effective leaching chemistry by defining chemical conditions in general (acidic versus alkaline) and pH, redox, and lixiviant composition in particular to optimize leaching kinetics for maximum productivity (finally to be evaluated by applying economic criteria, see below).

  Optionally, the wellfields could be pre-conditioned (e.g. by acidification before applying the actual oxidative leaching).

The wellfield design determines the achievable flow rate $Q$, usually quantified with reference to the effective pore volume $V_p$ (in the wellfield area under leach). The pore volume exchange (PVE) rate is defined by $q = Q/V_p$. The lixiviant flow fulfills to main functions: (i) transport of reactant into the orebody, and (ii) transport of leached metal out of the ore body.

The kinetic rate of leaching $r$ is the second determining parameter. It is quantifying the fraction of the actual metal mass in the reference ore volume that is leached per time unit. There is a straight mass (mole) balance of the injection rate of the reactant and the metal leaching rate. If the reactant injection rate is subcritical (i.e. too small), then a thermodynamic constraint could apply (to be demonstrated below) limiting the leachable metal mass per time unit.

Both $q$ and $r$ determine the achievable production rate (product of flow rate and metal concentration in the PLS) as function of wellfield operation time (cf. Figure 7).

The deposit criteria summarized in Figure 7 are subject to exploration and include, in addition to the ore morphology and hydrogeology of the deposit (usually accessed by geophysical surveying and drilling/borehole logging), mineralogical, chemical, and microbial aspects (based on core drilling and core assays mainly).

The determination and optimization of the wellfield design and leaching chemistry parameters are subject to reactive transport simulation (nowadays usually in 3D) with reference to dedicated lab and field tests (field leach trial FLT) throughout the well field in local and regional scale (wellfields embedded in the overall groundwater system).

State-of-the-art feasibility studies for ISR projects link the assessment of feasibility criteria as summarized in Figure 7 (in particular, by simulating the productivity/recovery during the lifetime of the wellfield by reactive-transport modelling) to appropriate economic models.
Figure 7: Summary of feasibility criteria regarding ISR application and corresponding conditions for wellfield design and performance
This approach is illustrated in Figure 8. The net present value (NPV) model links all cost factors (CAPEX/OPEX and any additional) to the revenue that is determined by the production rate related to the market price of the commodity. Deliverable D7.2 summarizes cost estimate approaches for ISR operations and metal processing. In deliverable D7.3, an enhanced NPV model is developed with regard to the specifics of the BIOMOre process.

2.2.3. Wellfield design

Prior to designing the appropriate wellfield (WF) pattern, the ore morphology and overall stratigraphy is determined in 3D by developing structural model(s). Using field data obtained from geophysical surveys and borehole logging, a 3D structural model is generated. This is then combined with a 3D regional scale flow model to optimize the WF parameters according to the deposit and aquifer characteristics. The WF geometry has to be adjusted to the ore body (also in the case of complex ore body structures, such as roll front deposits) in a way to ensure that

- The leaching solution has sufficient contact with the ore.
- The majority of the flow remains within the mineralized zone (avoidance of excursions and minimization of lixiviant migration).

The wellfield design, including operational parameters, is critical to ensuring an efficient leaching performance according to the hydrological deposit criteria (targeting an optimum interface between lixiviant and orebody). Pre-feasibility studies of an ISR project involve both 2D and 3D modelling of the ISR wellfield to optimize ISR processes and obtain cost estimates based on the:
- Wellfield geometry according to the ore morphology.
- Well spacing.
- Well screen length.
- All linked to the prediction of (well balanced) injection and extraction rates.

5-spot and 7-spot well field patterns are the most commonly implemented, with 4 or 6 injection wells surrounding one extraction well, respectively (cf. Figure 9). The distance between the extraction and injection wells (well spacing) typically ranges from 30 to 50 m (down to 15 m for high-grade orebodies).

![Wellfield patterns](image)

An example of typical flow path lines for a 5-spot wellfield at two different times after wellfield start-up is shown in Figure 10. Note that the wellfield has been embedded in the regional hydrological model to quantify the effect of the natural groundwater flow.

![Flow profiles](image)

The associated WF operation parameters, specifically the achievable WF flow rates and PVE rates, are investigated by applying state-of-the-art 3D hydrological models. Model parameters mainly influencing achievable flow rates include:

- Permeability.
- Thickness of the permeable horizon.
- Hydraulic head at the well location.
- Well spacing and screen diameter.

The well screen length and depth are dependent on ore body geometry mainly, however, also considering specific aquifer effects (heterogeneities, confinement). Ideally, the ore depth interval is fully screened to achieve optimum flow conditions throughout
the mineralized zone and minimize dilution effects (side flows). However, fully screening very thick deposits may result in a flow gradient along the screen and reduced integral leaching rates. In such cases, well rescreening may be an option (ISR practice).

Figure 10: Simulated wellfield flow pathlines (2D projection of a 3D flow model): 20 days after wellfield start-up (upper figure) and 3 years after wellfield start-up (code FEFLOW).

Injection and extraction rates are balanced, whereby the injection rate of a single well is adjusted to the number of extraction wells the flow contributes to. A well bleed of usually 0.5 to 2% is applied to a flow gradient towards the extraction wells and minimize migration of the leaching solution outside the leaching zone. Feasible flow rates are selected to maximize the contact between the leaching solution and the ore body, while preventing drawdown below the top of the extraction well screen. In order to estimate the resulting hydraulic head at the extractor screen, the Thiem equation can be used. For a 7-spot well pattern it reads:
\[ Q = \frac{2\pi \kappa T S}{\ln \left( \frac{0.8 A}{r_0} \right)} \]

where \( Q \) is the extraction rate, \( \kappa \) is the permeability, \( T \) is the aquifer thickness, \( S \) is the hydraulic head above the extraction well screen, \( R \) is the well spacing, and \( r_0 \) is the well screen radius. The fundamental dependences apply to other wellfield geometries as well; however, the geometrical factor has to be adjusted.

The unintended migration of the leaching solution outside the production area is both an environmental and economic concern. Regional 3D hydrological models (with “local” wellfields embedded as demonstrated above) are utilized to investigate and mitigate environmental impacts associated with ISR operations and to ensure that the leaching solution remains in the production zone. Additionally, the solution may spread outside the capture zone of the extraction well, with the leached metals being no longer accessible. Metals in these dead flow areas may be extracted by modifying the flow regimes. This may be accomplished, for example, by applying well role reversals, whereby injection wells become extraction wells, and vice versa. In special cases, (additional) infill wells could be considered to improve productivity.

The BIOMOre technology is intended to be used in fractured rock deposits (in contrast to classical ISR operations in sedimentary ore deposits). Fracturing and fracture modelling approaches are known from the oil and gas industry. A proper replication of the fractures within the model is problematic due to their difficult (or unavailable) visualization. A classification of simulation models is based on the incorporation of the heterogeneous fracture systems into the model which is the most challenging part in fracture modelling. The following three concepts can be distinguished (NRC, 1996):

- **Deterministic continuum models**: fracture heterogeneity is considered for a limited number of regions, each with uniform properties. Individual fractures are not explicitly entered in the model.

- **Stochastic continuum models**: fracture heterogeneity is represented as a continuous random field.

- **Discrete network models**: large numbers of individual fractures (geometry and properties) contributing to flow and transport are represented in the model. The scale of interest is smaller than normally considered in continuum models.

Whereas highly permeable sedimentary ore formations, e.g. hosted in sandstone, are characterised by a rather uniform free-fluid porosity enabling an ideal contact of the leachant with the metal-bearing minerals, the flow through fractured ore formations is preferential. In the latter case, the kinetics of leaching is by far more controlled by diffusion, thus, retarding recovery.

In order to optimize operational parameters and evaluate results from the pilot plant testing, a fluid flow simulation of the leaching block in the Rudna mine has been performed by using the finite element software FEFLOW. The implementation and model results of the leach block model are discussed in more detail in Chapter 6.
Moreover, the FEFLOW block leach model provides the input for the generic ISR code KiLea-Hy and allows for forecasting industrial-scale conditions, in particular, generalizing from block leach conditions to standard ISR (wellfield operation from the surface).

2.2.4. Leaching chemistry and kinetics

The leaching solution has to be composed in a way that it will dissolve the target mineral as efficiently as possible, i.e. highest leaching kinetics with lowest reagent consumption. The optimum leaching chemistry mainly depends on the mineralogy of the deposit (including both, the target mineral bearing the metal of interest and interfering minerals). In case of chemically reduced target minerals (e.g. sulfidic or uranium ores), the leaching solution has to fulfil two main tasks:

- Oxidation of the metal bearing mineral to dissolve the metal,
- Complexation of the metal of interest to strong aqueous complexes that remain in solution and hardly interact with the host rock.

**Acidic leaching** and **alkaline leaching** are distinguished based on the pH of the leaching solution. For uranium ISR, both operating regimes have been utilized. Typical reagents in use include sulfuric acid $\text{H}_2\text{SO}_4$ (in exceptional cases nitric $\text{HNO}_3$) in combination with ferric iron or oxygen (or any other alternative oxidant) for acidic ISR, or ammonia bicarbonate ($\text{NH}_4\text{HCO}_3$), sodium bicarbonate/carbonate ($\text{NaHCO}_3/\text{Na}_2\text{CO}_3$), or carbon dioxide ($\text{CO}_2$) in combination with oxygen for alkaline ISR. Table 1 summarizes the relevant characteristics of acidic and alkaline leaching of uranium. Similar conditions apply to the ISR of other (reduced) metals.

In copper ISR and heap leaching, acid leaching is common. Sulfuric acid, sometimes in combination with hydrochloric acid, is typically used. Furthermore, mixtures of organic acids (chemical leaching or bioleaching) are reported (Mulligan & Kamali, 2003). Alkaline leaching of Cu is known from gold leaching, with cyanide as a main competitor. Amino acids, e.g. glycine, at alkaline conditions have also been successfully tested at lab scale (Kutschke et al., 2015; Eksteen et al., 2017).

The pH value of the leaching solution constrains the utilization of the oxidant that can be applied. A very effective oxidant with a fast kinetic rate of oxidation is ferric iron. However, its applicability is limited to strongly acidic leaching due to the precipitation of ferric hydroxides or hydroxysulfates at $\text{pH} > 2$. The ferrous iron in the barren leach solution is usually re-oxidized to ferric iron by hydrogen peroxide (kinetics of oxidation by oxygen is quite slow). Other oxidants, like sodium chlorate, sodium hypochlorite, and potassium permanganate, are applicable (Davis & Curtis, 2007) but less common in ISR due to potential issues with regards to the subsequent processes. Oxygen is the common oxidant in alkaline ISR operations. In order to avoid a 2-phase flow in the leaching zone, $\text{O}_2$ is usually injected under high pressure to make sure that it is dissolved in the lixiviant (The solubility of oxygen depends significantly on temperature and pressure).
The selection between acid and alkaline leaching reagents depends on the following criteria (Lambert, 2010; Mudd, 1998; O’Gorman et al., 2004; Taylor, Farrington, Woods, Ring, & Molloy, 2004):

- Composition of the host rock and the ore, in particular, calcareous mineral abundance,
- Leaching efficiency (leach kinetics, maximum metal concentration in PLS),
- Environmental conditions in aquifer (e.g. GW quality, temperature, pressure),
- Reagent cost and consumption,
- Requirements from subsequent processing.

Table 1: Characteristics of acid and alkaline in-situ leaching for uranium

<table>
<thead>
<tr>
<th></th>
<th>Acid leaching</th>
<th>Alkaline leaching</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pH Oxidant Complexing agent</strong></td>
<td>pH &lt; 2 Fe(III) re-oxidized by O₂/H₂O₂ sulfate</td>
<td>pH &gt; 6 O₂ carbonate</td>
</tr>
<tr>
<td><strong>Typical recovery rates</strong></td>
<td>70-90%</td>
<td>60-70%</td>
</tr>
<tr>
<td><strong>Reaction kinetics</strong></td>
<td>Medium to high</td>
<td>Slow to moderate</td>
</tr>
<tr>
<td><strong>Concentration of total dissolved solids (TDS)</strong></td>
<td>High (10-25 g/L)</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Viability for ore with high carbonate abundance</strong></td>
<td>Limited</td>
<td>No constraint</td>
</tr>
<tr>
<td><strong>Material requirements</strong></td>
<td>Corrosion resistant</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Selectivity of leaching</strong></td>
<td>Medium (subject to chemical adjustments)</td>
<td>High</td>
</tr>
<tr>
<td><strong>Potential of contamination of subsequent processes</strong></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Effort in aquifer restoration</strong></td>
<td>High</td>
<td>Low to moderate</td>
</tr>
<tr>
<td><strong>Effort in water treatment</strong></td>
<td>High</td>
<td>Low to moderate</td>
</tr>
</tbody>
</table>

Dedicated lab tests (i.e. batch and column tests) close to in-situ conditions are always required to test and optimize the leaching efficiency according to the leachant composition. Often, numerical simulations (1D reactive transport models) of the leaching tests are applied to gather a detailed understanding of the chemical system and the kinetic dissolution parameter, which is the basis for upscaling to industrial scale ISR in
combination with 3D hydrogeological transport modelling. Figure 11 summarizes the various terms and dependences characterizing the kinetic rate of leaching. It is also applied to competing reactions (mineral dissolution and organics’ degradation).

\[
\text{Rate} = r_0 \cdot [H^+]^a \cdot [A^{e-}]^b \cdot [C]^c \cdot \exp\left(-\frac{E_a}{RT}\right) \cdot \left(\frac{v}{v_0}\right)^d \cdot f_{\text{bio}}
\]

- **[H\(^+\)]** – concentration of H\(^+\) ions related to the pH,
- **[A\(^{e-}\)]** – concentration of electron acceptors (oxidation potential),
- **R** – ideal gas constant,
- **T** – temperature,
- **v** - flow velocity (\(v_0\) – velocity reference parameter),
- **a, b, c, d** – parameters (specific for minerals),
- **r_0** – rate constant, specific for chemical reactions and dependent on mineral texture (inner reaction surface).

**Figure 11:** Generalized formula of the kinetic leaching rate and explanations.

The following conditions and trends have to be considered:

- The parameter “a” is positive for most silicate minerals (close to 0.5 for clay and feldspar minerals in particular), however, could also have negative sign (as for sulfidic minerals).
- For redox leach conditions the term [A\(^{e-}\)]\(^b\) is most important. b\(>0\) applies, i.e. the higher the oxidation potential the higher the leach rate.
- The dependence on the concentration of the complexing ion [C] is usually applied for alkaline leaching of reduced uranium minerals. In the acidic case, it is implicitly considered by the dependence on [H\(^+\)] in correlation [SO\(_4\)].
- The Arrhenius term expresses the temperature dependence of chemical reactions.
- The consideration of the (empirical) Damkoehler number might be important, however, is dependent on the reactive-transport model applied (consideration of dual-porosity approach).
- In the case of bioleaching, the Michaelis-Menten kinetics for enzyme kinetics might be considered. It describes the effect of decreasing the activation energy of a chemical reaction by microbiologically generated enzymes (cf. Figure 12).
2.2.5. Reactive transport – combination of wellfield hydrology and leaching chemistry

ISR is the combination of hydrology (lixiviant flow) and leaching chemistry/kinetics (interaction of the lixiviant with the metal-bearing mineral(s) and other mineral constituents in the ore. Reactive transport models describe this complex process accordingly (WP2 deliverables and references therein).

Hydrological flow and reactive transport models based on in-situ field conditions are used to realize the WF parameters necessary to maximize metal recoveries and predict WF performance. The reactive transport parameters (kinetic dissolution rates) are based on an understanding of the leaching chemistry gained from column leach tests in the laboratory in an early stage of project development, later verified by a field leach trial FLT. The appropriate kinetic parameters are determined by parameter fitting of experimental results (data from literature/references needs to be validated for the specific site conditions).

For the 3D wellfield model, the kinetic rates determined in lab tests are applied, while hydraulic properties are up-scaled based on exploration data and field leach trials. The flow regime in combination with the leaching chemistry yields a production rate as a function of time. Ideal oxidant concentrations and flow rates for optimal metal recovery can then be determined through parameter variation studies. Additionally, hydrogeological model parameters are varied to determine the effects of varying conditions on the resulting recoveries. This enables the recovery rates, and thus production rates, to be optimized and more reliably predicted according to site conditions, and ultimately used for the economic evaluation of ISR projects.

In dependence of the complexity of the ore morphology, the heterogeneity of the hydrogeology of the host aquifer, and the state of exploration, the 3D wellfield model is...
further adjusted with the progressing wellfield operation to optimize the wellfield parameters in accordance to the local conditions.

2.3. Economic attributes, potentials and challenges

2.3.1. Potential

As it is known from uranium mining, ISR can be an economic alternative to conventional mining technologies (open pit, underground mining), if hydrogeological settings meet the requirements summarized in Figure 7. For uranium ISR in a shallow deposit, the capital investments for ISR are significantly (up to several times) less compared to conventional open pit or underground mines. This is associated with several advantages (Seredkin et al., 2016):

- Lower development costs for the mine, processing plant, and infrastructure.
- Ability to start production at a low capital cost with a following increase in production. In particular, allowing for using profits from the cash flow instead of debt financing funding the mine development in advance.
- Greater flexibility in production capacity (easier capacity reduction during lower price periods and increased capacity when prices are high).

In addition, ISR has the potential for reducing Capital Expenditures (CAPEX) for infrastructure and mine development and Operation Expenditures (OPEX) for water, energy, and personnel. In particular, ISR (if applied professionally and if site conditions are appropriate) could be operated at reduced environmental impacts and reduced requirements for remediation (IAEA, 1992; O’Gorman et al., 2004):

- (In the case of uranium ISR) Reduced personal radiation exposure (less dust emission).
- No creations of open holes, waste dumps, leach ponds, or tailings (MM1, MM3)\(^1\).
- Less waste generation, less environmental impact (when properly conducted).
- No ore or waste moved (G4-EN3, G4-EN15)\(^1\).
- Minimal visual disturbance (G4-SO2)\(^1\).
- Minimal noise, dust, greenhouse gas emissions, and other emissions (G4-SO2, G4-EN15, G4-EN21)\(^1\).
- Often faster and less expensive mine closing and remediation.

Furthermore, the reduction of CAPEX/OPEX has the potential for economically feasible mining of even low grade deposits using ISR.

\(^1\) from D5.1, in brackets the relevant SDI (sustainable development indicator)
Based on the economics known from ISR uranium projects, cut-off concentrations in pregnant solutions, capital costs and full production costs, as well as cut-off grades and productivity cut-offs for the resource estimation of ISR projects of various metals have been approximated as summarized in Table 2 and Table 3.

Table 2: Indicative estimation of economical parameters for ISR projects (Seredkin et al., 2016)

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Prices (US$)</th>
<th>Pregnant solutions</th>
<th>Indicative estimation of economical parameters</th>
<th>One mineralisation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cut-off grade</td>
<td>Accepted options for estimation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>mg/l</td>
<td>Capacity mg/l</td>
<td></td>
</tr>
<tr>
<td>Uranium</td>
<td>$35/Lb</td>
<td>28</td>
<td>3.2–5.5</td>
<td>100 t</td>
</tr>
<tr>
<td>Copper</td>
<td>$5000/Lb</td>
<td>510</td>
<td>0.15–0.5</td>
<td>60–145</td>
</tr>
<tr>
<td>Gold</td>
<td>$1100/oz</td>
<td>0.07</td>
<td>1.5–17</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Nickel</td>
<td>$10,000/oz</td>
<td>255</td>
<td>10.0–40</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>$13,000/oz</td>
<td>165</td>
<td>2.0–4.0</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Scandium</td>
<td>$3000/kg</td>
<td>0.7</td>
<td>3.6</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Rhenium</td>
<td>$85/oz</td>
<td>0.95</td>
<td>0.8</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Vanadium</td>
<td>$20/kg</td>
<td>127</td>
<td>0.5</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Scandium</td>
<td>$15/Lb</td>
<td>65</td>
<td>0.5</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Rare Earth</td>
<td>$19/kg</td>
<td>134</td>
<td>0.7</td>
<td>1000 kg</td>
</tr>
</tbody>
</table>

*155/192RE; 59/144Hf REE and Y.

Table 3: Indicative estimation of cut-off grades and productivities for ISR projects (Seredkin et al., 2016)

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Cut-off grade, mg/l</th>
<th>Extraction 50%</th>
<th>Extraction 70%</th>
<th>Extraction 90%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Units</td>
<td>L5 = 3</td>
<td>L5 = 5</td>
<td>L7 = 7</td>
</tr>
<tr>
<td>Uranium</td>
<td>28</td>
<td>0.017</td>
<td>0.028</td>
<td>0.039</td>
</tr>
<tr>
<td>Copper</td>
<td>1.1</td>
<td>0.306</td>
<td>0.510</td>
<td>0.714</td>
</tr>
<tr>
<td>Gold</td>
<td>0.04</td>
<td>0.470</td>
<td>0.70</td>
<td>0.79</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.95</td>
<td>0.153</td>
<td>0.255</td>
<td>0.357</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.5</td>
<td>0.118</td>
<td>0.196</td>
<td>0.274</td>
</tr>
<tr>
<td>Scandium</td>
<td>0.1</td>
<td>0.076</td>
<td>0.127</td>
<td>0.178</td>
</tr>
<tr>
<td>Rhenium</td>
<td>0.03</td>
<td>0.039</td>
<td>0.065</td>
<td>0.091</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.03</td>
<td>0.089</td>
<td>0.134</td>
<td>0.188</td>
</tr>
<tr>
<td>Scandium</td>
<td>0.12</td>
<td>0.039</td>
<td>0.065</td>
<td>0.091</td>
</tr>
</tbody>
</table>

It is shown that in addition to uranium and copper, metals such as gold, nickel, vanadium, and selenium can be profitably mined by ISR based on the estimated levels of metals in productive solutions. In contrast, molybdenum, rhenium, scandium and rare earth elements are only likely to be mined as by-products with uranium as the predicted concentrations in PLS are not high enough for profitable operations. Guidelines for the selection of mineral deposits suitable for ISR were developed following cut-off grades (Seredkin et al., 2016):

- Copper: 0.2%
- Gold: 0.25–0.3 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%
- Rare Earth Elements: 0.05 – 0.06%

2.3.2. Challenges

The basis of a successful ISR operation is the field exploration with regards to the deposit criteria in combination with the detailed understanding of the ISR operational parameters affecting the ISR performance. The numerical simulation of hydrological and chemical leaching processes could be very valuable to assess the feasibility of ISR for the given deposit and to develop the best site-specific technology approach. Essentially, ISR is an “invisible” mining approach, i.e. the ore is not recovered, but the operation is performed from the surface based on the hydrogeological information, deposit conditions and other information gathered during the exploration and project development phase and subject to process monitoring during the ISR operation. Parameter uncertainties are more significant than in conventional mining operations. Hence, the effort increases for continuously adapting the in-situ operation for optimum recovery. Challenges of ISR include (O’Gorman et al., 2004):

- Decrease in recovery by reduced contact between leaching solution and mineralization.
- Environmental impacts by leachate escape outside the mining areas (G4-EN22)1.
- Seismic and rock mechanic impacts (G4-SO2)1.
- Increased time span for metal extraction than conventional mining.
- Insufficient hydraulic pressure for extraction of PLS.
- Insufficient confinement of the aquifer.
- Ores located above the water table (crucial for ISR and environmental protection).
- Post-operational chemical or microbial impacts on the deposit (MM3)1.
- Increased permitting effort.

2.3.3. Interfering effects

The type of mineralisation can strongly affect the leachability of the metal(s) of interest. First, the leachant could interact with other (gangue) minerals. Second, a mineral matrix (texture) with the mineral of interest incorporated in a complex structure (mineral intergrowth) could inhibit or at least retard leaching significantly. Another critical factor could be the absorption, whereby a high absorption (e.g. peat or coal) makes ISR impossible (Seredkin et al., 2016).
Gangue dissolution/precipitation reactions can negatively affect leaching processes. For example, the leaching of gangue minerals, such as biotite or carbonates, results in an accumulation of undesirable cations in the solution, including magnesium, aluminium, potassium, and calcium. Ions may also be released from clays or other adsorptive minerals due to their ion exchange capacity (cation exchange capacity CEC of clays, anion exchange capacity AEX of gibbsite, hematite and other minerals generated after strong weathering). These ions are not removed in the metal recovery step and, thus, they are re-injected into the ground and accumulate over time. This can cause a re-precipitation that blocks the fractures and prevents both a homogeneous flow and effective leaching of the rock. Further, these ions can influence the pH, the PVE rate, and the oxidation potential. Common for such precipitates are gypsum, which forms from excessive calcium built-up, and jarosite, caused by excessive levels of ferric iron and alkali metals. When such precipitates form, the restoration of ISR projects may take more time, as re-dissolution of these precipitates can occur during the rinsing process (Sinclair & Thompson, 2015).

Interfering side reactions can be reduced or even avoided by maintaining a bleed stream to reduce cation built-up or by the use of chemical inhibitors (e.g. gypsum inhibitors). Gangue mineral dissolution is generally positively correlated with acid concentration; lower acid concentrations may help to reduce side reactions. Also, alkaline leaching systems can be an alternative to reduce side reactions; this is applied for uranium ISR in the US (Sinclair & Thompson, 2015).

Clays can cause specific problems for ISR operations. In addition to the chemical effects of cation exchange (CEC), swelling or even disintegration of clays can occur when the lixiviant is less saline than the pre-existing groundwater. This can result in a decreased permeability. Some of these reactions may be avoided by pre-flushing with specialized solutions (Sinclair & Thompson, 2015).

In addition to clay, chemical reactions during the leaching process can influence the permeability. An increase or decrease of the permeability can occur depending on the net effect and whether there is a flow channel widening from mineral dissolution or a flow channel constriction from precipitation reactions and/or clogging with suspended particles. This effect is related to the geology and mineralogy of the ore deposit (Sinclair & Thompson, 2015).

Re-precipitation, secondary enrichment and sorption of the metal of interest, e.g. copper, can also significantly impact recovery. Further, a high salinity, e.g. due to chlorides, will influence bioleaching reactions, because it inhibits the microbial growth and, thus, will limit the provided oxidation potential.
2.4. ISR block leaching as a special case

The operation of ISR wellfields from the surface is the common industrial standard. Block leaching applications were developed and operated in exceptional cases as summarized in (UIT, 2016).

In general, underground block leaching can be performed in mines using the existing infrastructure to provide easy access to the ore. Usually, the ore is virtually divided in blocks for leaching, hence the name: block leaching. Due to the dewatering of the underground mines, the ore is unsaturated. The leaching solution is injected on top of the block and percolates downwards, driven by gravity, to the drainage system at the bottom of the block where the PLS is extracted.

Three main types of underground leaching operations were applied in the past: (i) hydrodynamic leaching, (ii) hydrostatic leaching, and (iii) section leaching. In addition, combined methods can be applied, where hydrodynamic leaching for injection (permeable sandstone with drill hole system) is combined with fractured (drilling and blasting of less permeable interbedded strata) sections at the bottom of the block for drainage.

The **hydrodynamic leaching** is applied for the leaching of permeable, bed shaped ore repositories, e.g. permeable sandstone. A coherent flow of solution either continuous or periodic fills all chasms and pores of the deposit. Pressure differences between leachant injection and drainage system drive the solution to move. Leaching occurs due to interaction of the percolate leachant with the mineral surfaces and by diffuse mixing of the solutes in the pore solution when a concentration or pressure gradient is present. Leaching kinetics of the deposit depends on (i) the composition of the leachant, (ii) the permeability of the deposit, (iii) the pressure, and (iv) the infiltration coefficient of the solution flowing through the rock. Injection of leachant in the hydrodynamic scheme can be either over a system of injection holes (small injection pressure) or by sprinkling (similar to heap leaching). If injection is performed by sprinkling it is referred to as infiltration-capillary leaching. It is an extensive long-term process which lasts in most cases over several months.

**Hydrostatic (immersion) leaching** is well applicable to ores with low permeability, e.g. clayey sandstone. In case of hydrostatic leaching the ore block is flooded with solution continuously or periodically. Therefore, a confined leaching section is necessary. Leaching occurs only by diffusion due to the very low infiltration coefficients of the ore. As there are nearly no convective processes the leaching is very slow.

For **section leaching** injection and drainage of the leaching solution is performed by horizontal drillings (system of injection and drainage holes as fan). It is applied to less permeable lithologies at a typical injection pressure of about 0.6 MPa.

Block leaching could be an alternative under the following conditions:

- Mining of low grade ore in an already present underground mine.
- Mining of low grade ore no longer economic mineable by conventional mining.
• Mining of hard rock, where fracturing is used to increase permeability.

The operating Rudna mine in Poland was selected as the test site within the BIOMOre project because this mine is located in consolidated rock – Permian Zechstein Cu unit – (low permeability and porosity) and at a large depth (~1,000 m depth). The mining alternatives within an operating mine are limited and, thus, block leaching was chosen to demonstrate the viability of the BIOMOre process.
3. The BIOMOre process

The BIOMOre process is the indirect in-situ bioleaching of sulfidic ore as an alternative mining technology to minimize environmental impacts and to reduce waste generation. It has been considered as an environmentally friendly bio-mining process that could be a cost-effective alternative to a pure chemical ISR approaches.

One of the options of ISR in general and the BIOMOre process in particular is the permeability enhancement in order to apply the technology to more consolidated ore categories. Technologies developed in the oil & gas industry will be summarized in Section 3.1.

Bio-mining of sulfidic copper ore is industrial practice in heap leaching in particular. Microbes catalyse the oxidation of ferrous iron to ferric iron leading to a significant increase of the reaction kinetics. The potential of in-situ bioleaching is described in Section 3.2.

Figure 13 illustrates the basic BIOMOre approach, i.e. the biotechnological oxidation of ferrous to ferric Fe by utilizing an on-surface ferric iron generating bioreactor (FIGB). In addition, the present report considers optional stimulated in-situ bioleaching by oxidant injection (the analogue to bioleaching in tank or heap applications).

3.1. Permeability enhancement

One of the most important factors defining the economic suitability of an ISR project is the permeability that is related to the porosity in dependence on the microstructure of the ore. The permeability enhancement should result in an increased lixiviant flow rate and, hence, in an increase of the production rate.
Permeability enhancement techniques were developed in the oil & gas industry and successfully applied to increase recovery. The achieved increase of production flow rates is in the order of several $10^1\%$. The effect on the porosity is limited by the incompressibility of the ore.

### 3.1.1. Summary of permeability enhancement techniques

Various techniques for permeability enhancement have been developed. Figure 14 summarizes the main characteristics of the most important ones: **hydraulic fracturing**, **acidizing**, **thermal fracturing**, and some other techniques including stimulation by explosives, by acoustic waves and by electric effects. **Drilling & blasting** is exceptional and has only been applied to prepare ore blocks for ISR leach (here, a compensation volume is available to rubberize the ore, i.e. to create voids/pores and to increase the porosity).

---

**Figure 14: Overview of permeability stimulation options**

The standard techniques vary in the rate at which energy is applied to the target horizon. Typically, this rate is inversely proportional to the mass of the treating fluid. For example, hydraulic fracturing (HF) uses a relatively low rate of loading that results in a two-winged vertical fracture extending outwards from a well with a perpendicular orientation to the least principal rock stress, as shown in Figure 15.
3.1.2. Hydraulic fracturing

In general, the maximum hydraulic fracturing pressures exceed the minimum in-situ rock stress slightly. As hydraulic fracturing (HF) produces only long, single fractures, it allows for pumping large fluid volumes at relatively low rates, i.e. achieving penetration in the order of tens to hundreds meters (Advanced Resources International Inc., 1999). The efficiency of HF is highly dependent on the in-situ stress state and nature of the ore deposit (i.e. geochemical contrast required between “hard host rock and softer veins”). But under favourable conditions, HF can be an asset. The hydraulic fracturing process applies a hydraulic pressure on the rock formation until the formation fracturing pressure or “breakdown pressure” is overcome. It is usually performed in two stages:

1. Pad stage: Injection of the hydraulic fracturing fluid (mainly water) to breakdown the formation and initially create a fracture and to reduce fluid loss.
2. Slurry stage: Injection of the slurry, a mixture of the fracturing fluid and propping solid material (“proppant”).

The proppant, e.g. sand, prevents the closure of fractures. There are three hydraulic fracturing concepts:

- Hydraulic Proppant Fracturing (HPF) uses highly viscous gel as a fracturing fluid with high proppant concentration to conductive, relatively short fractures in a porous matrix formation.
Water Fracturing (WF) uses water containing, friction-reducing chemicals partially added with low proppant concentration as a frac fluid to create long and narrow fractures.

Hybrid Fracturing combines fracture stimulation using different gels and slick water fluids as the fracturing fluid. It utilizes the advantages of HPF and WF in creating the fracture geometry and in the effective placement of the proppant into the far-end of the induced fracture (Aqui & Zarrouk, 2011).

As explained in deliverable D2.3, hydraulic fracturing for field applications is still under development. Hydraulic fracturing is related to some risks in addition to the normal risks of gas extractions. These risks are, as explained in deliverable D5.3:

- Large quantities of chemicals used during the process of hydraulic fracturing.
- Selection of chemicals including toxic, carcinogenic and mutagenic substances, and substances harmful to the environment used as additives for fracturing fluids (e.g. biocides).
- Amount of flow back water contaminated with radioactive substances such as radon and uranium and other additional subsurface materials (e.g. heavy metals).
- Large number of drilling sites.
- Infrastructure e.g. network of gathering pipes.
- High amount of water used for the fracturing fluid.
- Potentially high emissions of methane from well completion.

Additionally, unforeseen incidents due to the interaction between pulse gas and the following bioleaching reactions may arise. Thus, a decision for this technique must be made carefully.

### 3.1.3. Explosive fracturing

Explosive fracturing is the other extreme compared to the energy rates. It involves a very rapid loading of the target formation which results in a highly fractured zone, but with a smaller extent (radius < 3 m). Because the peak pressure exceeds all in-situ stresses, fractures are created in all three dimensions. Unfortunately, the peak pressures of explosive fracturing can also exceed the rock yield strength, which can cause compaction to such a degree that the permeability is actually decreased in the near-well region, resulting in a damaged zone.

### 3.1.4. Pulse fracturing

Between the two previously explained fracturing techniques, pulse fracturing techniques can be categorized. These include:
• High-energy gas fracturing with propellants that reaches a peak pressure within a few milliseconds that exceeds the maximum in-situ stress. However, this pressure does not exceed the rock yield stress and, thus, avoids the damage associated with explosive fracturing. With this technique, multiple vertical fractures are produced (2 to 7 m radially).

• Extreme overbalance fracturing shows a smaller pressurization rate and pressure magnitude. In fact, the degree of radial fracturing may be less; sometimes, no radial fractures may be achieved at < 7 meters (Advanced Resources International Inc., 1999).

3.1.5. Acidizing

Two acidizing techniques are common:

• Matrix acidizing.

• Acid fracturing.

They differ in the pressure at which acid is pumped into the formation relative to the “fracturing pressure” of the reservoir formation. Thus, in matrix acidizing, acid is injected at pressures below the formation fracturing pressure. It is usually conducted in three stages:

1. Pre-flush: Injection of 5 to 15% hydrochloric acid (HCl) to dissolve carbonate minerals in the formation to avoid precipitation in the next stage.

2. Main-flush: Injection of a “mud acid” (mixture of HCl and HF); HCl is able to dissolve limestone and dolomites, while HF can dissolve siliceous minerals such as clays, feldspar, and silica sands.

3. Post-flush: Performed with fresh water or with other chemicals to push the main-flush acid mixture further into the formation and minimize precipitation reactions near the well.

Acid fracturing is performed at a pressure greater than the formation fracturing pressure to stimulate an undamaged formation. It is related to hydraulic fracturing as both have the objective to create long, open, conductive channels and have the same basic principles of fracture propagation. Acid is either injected to create fractures or into a fracture that was created by a viscous fluid, e.g. gel (“pad”) (Aqui & Zarrouk, 2011).

3.1.6. Thermal fracturing

Thermal fracturing is a variation of hydraulic fracturing, but it relies on the thermal contraction induced by significant temperature differences between the cold fracturing fluid and the hot rock formation instead of hydraulic pressure to create new fractures. As the pumping pressure is relatively low, there is no hydraulic fracturing.
Other techniques are available that are not so common, e.g.:

- Casing perforation: designed to access cased-off permeable horizons by perforating well casing.
- Acoustic stimulation: use of ultrasonic waves to cause changes in the permeability or removal of plugging materials.
- Electric stimulation: use of an electric current to stimulate the well to create either an electrothermal or an electrodynamic effect (Aqui & Zarrouk, 2011).

3.1.7. Viability of permeability enhancement for ISR

3.1.7.1. ISR well field operation

The techniques explained above could be subject to operational and environmental problems. In particular, if a chemical is injected into the underground, the corresponding contaminations could result in environmental issues. On the other hand, precipitation of secondary phases could clog well screens and formation pores and affect the well performance during leaching.

Permeability enhancement results in limited improvements by creating fractures and/or connecting (formerly isolated) pores (incompressibility of rock). Accordingly, the increase of porosity is marginal.

Potential favorable deposits for permeability enhancement might be:

- Deposits where the majority of the mineralization is located on the surface of permeable veins. In this case the fracturing connects the veins further and significantly increases the contact between leaching solution and mineralization. Simultaneously, a sufficient natural porosity will be present with respect to the veins.
- Highly fractured deposits with sufficient porosity and permeability where fracturing might increase the contact surface between leaching solution and rock/minerals.

If fracturing is considered for permeability enhancement, it should be kept in mind that, in contrast to oil & gas mining, ISR requires a targeted flow of leaching solution between injection and extraction wells over a long period of time (including many pore volume exchanges).

3.1.7.2. Block leaching

The conditions for permeability enhancement are much improved in the case of block leaching in an underground mine. A compensation volume to enable both porosity and permeability enhancement can be immanent part of the (geophysical) pre-conditioning design.
Permeability enhancement as part of the BIOMOre technology has been tested in the Rudna mine. However, the (high-pressure) HF could not be applied for the following reasons:

- The formation at the test site is unsaturated, thus, prior to HF, an injection of the equivalent of the effective pore volume in the sediment rock would be necessary followed by the actual HF at a typical operating pressure of several 100 MPa. There was no backpressure from a (typically saturated) formation to effectively build up the in-situ pressure.

- Injected water could migrate in all directions (under the pressure relevant for HF), saturating the formation within a wide range and also risking an uncontrolled discharge into the drift system of the Rudna mine.

Due to these reasons, ‘drilling & blasting’ was selected as the permeability enhancement method for the test site, since:

- Costs (considerably lower than for HF in the present case) could be limited.
- Efficiency of drilling & blasting (about 75 % of chemical energy of explosives will be consumed for rock fragmentation) has been exploited in a controllable block volume.
- Blasted rock has shown up a connected fracture network, leading to a significant penetration of pressurized leaching fluids.
- Environmental impact of drilling & blasting could be limited (less water consumption compared to HF).
- Compensation volume could be created prior to fracturing to achieve more fractures.

3.2. Potential of bioleaching in ISR

Bioleaching refers to the mobilization of metal ions from ores through biological oxidation and complexation processes. It is used in industrial heap and tank leach applications for the recovery of metals, such as Cu, Co, Ni, Zn, and U, from reduced ores.

3.2.1. Microbial processes used for bioleaching

Three main processes occur on the interface of bacteria or fungi and minerals:

- Acidolysis: Formation of organic or inorganic acids.
- Redoxolysis: Oxidation and reduction reactions.
- Complexolysis: Formation of complexing agents.

Mixtures of organic acids have been reported for effective bioleaching of rare earth elements from monazite, e.g. citric, oxalic acid. In leaching environments sulfuric acid is the main inorganic acid, which can be formed by sulfur-oxidizing microorganisms.
such as acidithiobacilli (Brandl, 2001). Deliverable D1.2 discussed the potential option to produce sulfuric acid in a sulfuric acid-generating bioreactor (SAGB). This would be a greener technology as no transportation of acid would be necessary. Nevertheless, an additional sulfur source would be required and the economics of such a SAGB mainly depends on the retention time.

The BIOMOre process focuses on redoxolysis. The mineral dissolution of copper sulfides is a redox process and requires a sufficient amount of electron acceptors (oxidants). Microorganisms catalyse this oxidation process, if electron acceptors are available. The kinetic rate of the oxidation could significantly increase.

The bioleaching of reduced minerals can be categorized into direct and indirect leaching, as shown in Figure 16.

![In-situ bioleaching of reduced minerals](image)

Figure 16: Systematics of bioleaching of reduced (e.g. sulfidic) minerals

Only the *indirect* mechanisms have been validated to be practicable (either contact, non-contact, or cooperative leaching). Depending on the chemical conditions of the leaching solution, two “indirect” pathways/mechanisms are proposed:

- The thiosulfate mechanisms at alkaline conditions with thiosulfate as main intermediate formed by the oxidation e.g. of pyrite, molybdenite, tungstenite.
- The polysulfide mechanisms under acidic conditions with polysulfide and elemental sulfur as main intermediates formed by the oxidation e.g. of galena, sphalerite, chalcopyrite, chalcocite, orpiment, realgar.

At a low redox potential, elemental sulfur may form a layer on the mineral surface, inhibiting the diffusion rates for ions and oxygen (Brandl, 2001; W. Sand, Gehrke, Hallmann, & Schippers, 1995; Vera & Schippers, 2013).
3.2.2. Industrial practice of ISR vs. bioleaching

Whereas bioleaching has been clearly demonstrated in tank and heap leaching applications using aeration to provide the oxidant (now industrial practice), in-situ bio-leaching is currently undergoing intensive research. In heap and stope leaching, the injection of microorganisms for the stimulation of bioleaching has been practiced and the supply of the ore with O₂ can be easily done by ventilation with air (aeration) and is quite cheap (Wolfgang Sand, Hallmann, Rohde, Sobotke, & Wentzien, 1993).

In industrial acidic ISR applications, it is common to apply ferric iron as oxidant, i.e. Fe(III) = 2 to 5 g/L (corresponding to [A] = 36 to 89 mmol/L). Ferric iron Fe(III) is reduced to ferrous Fe(II) in the PLS during mineral dissolution. Therefore, prior to re-injection, the leaching solution is re-oxidized, typically by a controlled H₂O₂ dosage. This re-oxidation can be performed by microorganisms that use oxygen as oxidant.

The two considered options of bioleaching are stimulated in-situ bioleaching and ex-situ bio-oxidation. In in-situ bioleaching, the oxidation occurs in the underground catalysed by stimulated native or cultured microorganisms, while in the ex-situ case it occurs in a ferric iron generating bioreactor (FIGB) at the surface.

The bioleaching efficiency is determined by (Brandl, 2001):

- Physicochemical parameters of the bioleaching environment, e.g. pH, ORP, O₂, CO₂, temperature, pressure, nutrients.
- Microbiological parameters of the environment, e.g. microbial diversity, microbial activities, metal tolerance.
- Properties of the mineral, e.g. mineral composition, grain size, porosity.
- Processing, e.g. leaching mode (in-situ, heap/dump, or tank) and related parameters like stirring rate or heap geometry.

Physicochemical parameters define the living conditions for microorganisms. The availability of the oxidant O₂ is crucial for the re-oxidation of Fe by microorganisms to enable indirect bioleaching.

The injection of microorganisms in an ISR operation is challenging due to the specific underground conditions (temperature, pressure, salinity, interfering minerals or other constituents, microbial diversity etc.). High pressures can cause microorganisms to become inactive (cf. deliverable D1.3).

If the environmental conditions are favourable, a homogeneous distribution of the microorganisms over the leaching zone and the supply with oxygen and nutrients needs to be ensured. Biological oxidation on the surface of the ore particles has been used in the leaching of fragmented copper ore with sufficient atmospheric contact. In-situ bio-oxidation of sulfide minerals is also currently developed for ISR of gold ores. Bacterial oxidation in the subsurface is possible on principle. The required co-injection of oxygen is a limiting factor for this process (solubility criterion for O₂ as discussed...
above). Additionally, a significant lag time has to be considered for adaption of the microbial system to the changed conditions.

Finally, uncontrolled biological reactions may negatively affect the flow properties, e.g. fouling, gypsum precipitation (cf. deliverable D1.3). In addition, specialized ferric iron reducing allochthonous microbes may change the environmental conditions in the deep surface, e.g. by acidification or by heavy metal ion mobilization (cf. deliverable D1.5).

The monitoring of microbial activity in ISR applications is difficult and has rarely been carried out systematically. Until now, the focus was mainly on the investigation of microbial post-ISR effects because natural attenuation is accompanied by microbial activity (immobilization of metals).

In contrast, ex-situ bio-oxidation has the following main advantages:

- The supply of oxygen and nutrients can be optimized independent on the aquifer conditions and leachant flow rate.
- The risk of microbes clogging the pores is reduced.
- Microbial growth can be controlled.

Therefore, the BIOMOre process integrates the ex-situ bio-oxidation as indirect bio-leaching. In-situ block leaching of copper in combination with an ex-situ bioreactor for the re-oxidation of Fe$^{2+}$ to Fe$^{3+}$ has been tested and conceptually up-scaled to well field-based ISR of any metals from reduced ores (Johnson, 2015).

The pilot test bioleaching was performed in 3 stages:

- Phase 1: Water flush to remove soluble salts (exceptional stage, but applies to Rudna mine conditions in particular).
- Phase 2: Sulfuric acid pre-conditioning to reduce the pH for ferric leaching by removing calcareous minerals and other acid-soluble constituents.
- Phase 3: Oxidative leaching (indirect bioleaching) by using a microbiologically generated ferric iron leachant.

The bioleaching application using air or O$_2$ has to be compared with the industrial operation mode using H$_2$O$_2$ from an economic point of view. Therefore, the retention time of the leach solution to oxidize Fe$^{2+}$ to Fe$^{3+}$ by microorganisms is the main parameter. As shown in lab experiments, the hydraulic retention times (HRT) for a solution with 50 mM Fe are between 5 and 33 h (Pakostova, Grail, & Johnson, 2017). This translates into the required FIGB tankage at given lixiviant flow rate. Thus, for an economic application, further optimization is necessary.
3.2.3. Challenges of bioleaching applications

Most acidophilic iron oxidizers are inhibited by high chloride concentrations that could occur in ore bodies (Vera & Schippers, 2013). High chloride concentrations in the Rudna Mine test block demanded the water flush phase in the pilot test bioleaching. In addition, toxic metals could inhibit the growth of microbes.

Also, there is a concern of uncontrolled biological reactions occurring in the ore deposit by bioleaching. Even when ex-situ bioleaching is performed, some microbes could be associated with the ferric solution and become injected in the subsurface.

For minimization of the aftermath of bioleaching, chemical compounds can be applied that either show biocidal or bacteriostatic effects. Such compounds can be biocides, surfactants, chlorides, quaternary ammonium compounds, organic solvents, or even organic compounds (cf. deliverable D1.5).
4. Generic kinetic leach model KiLea-Hy for case studies and as a basis for economic assessment

4.1. KiLea-Hy background and adaption to BIOMOre

KiLea is a proprietary software tool developed by UIT and used for predicting ISR performance in the uranium mining industry as well as for optimizing the recovery during wellfield operation. It combines the following main functions:

- Prediction of ISR performance for new ISR wellfields. Scenario studies as function of operational conditions (optimization in advance).
- Retrospective reproduction of the ISR wellfield performance of running wellfields (i.e. using real operational data on wellfield hydrology and lixiviant chemistry as input).
- Forecast of remaining recovery from running wellfields as function of operational parameters (optimization in the course of active mining).

KiLea is combined to an economic model to assess wellfield operation parameters for maximizing economic productivity finally. In parallel, 3D hydrological and reactive-transport models are run for securing environmental compliance. KiLea is a 1D reactive-transport model linked to a thermodynamic/kinetic database (optional adjustment of parameters with reference to test results) on the one side and to the operational database for retrospective modelling on the other side. KiLea has been generalized (now KiLea-Hy) for the BIOMOre project with regard to:

- Consideration of various ISR applications, keeping U ISR as a valuable reference, but enabling its application to different Cu ores (e.g. chalcocite), Zn ores (e.g. sphalerite) and others (optional extension).
- Whereas the base version has been developed for acid ISR, U ISR can be simulated also for the alkaline conditions (optional extension to oxide ores).
- In addition to wellfield-based ISR, the (percolate) block leaching case has been implemented to enable the simulation of the Rudna test case. Whereas approximate formula are applied to estimate hydrological conditions (flow rate and pore volume exchange rate), full-scale 3D hydrological models can be applied to validate the estimates. Some KiLea-Hy algorithms were based on such detailed 3D hydrological modelling (in particular, the effect of wellfield spacing on the effective ore volume under leach and finally, on recovery).

For the application within BIOMOre, KiLea-Hy considers input data from the work packages WP1 (lab data), WP2 (complex modelling results) and WP3 (Rudna field test data). It is a suitable software tool for the systematic study of feasibility criteria with regard to BIOMOre technology applications, easy to use (Excel based user interface), and linked to an economic ISR model to extend the generalized feasibility study to revenue and cost figures (applied in Task 7.2).
4.2. Hydrogeological baseline conditions

The porosity and the related permeability are key parameters determining the possible hydraulic conditions in any ISR operation. In addition, heterogeneities of these parameters within the orebody under leach might constrain the recovery significantly (limited contact between lixiviant and mineralization of interest). For standard ISR applications within sedimentary formations, an empirical relationship between (free-fluid) porosity (i.e. excluding non-connected pores and \( \mu \)-pores) and permeability is applied, if relevant data is missing (otherwise such data is used as direct input).

Figure 17 illustrates the variety of the porosity-permeability relationship as function of lithological conditions with reference to the Kozeny-Carman equation:

\[
\kappa = \tilde{\alpha} \frac{\varepsilon^3 D_p^2}{(1-\varepsilon)^2}
\]

Where the parameter \( \tilde{\alpha} \) has to be determined by lab testing (dependent on lithology, in particular, the degree of cementation by carbonates, silicates or other), and \( D_p \) is the average diameter of mineral grains. KiLea-Hy enables the adjustment of parameter \( \tilde{\alpha} \) for generic simulations of ISR in a specific lithological category.

Figure 17: Systematics of the porosity-permeability relationship as used in KiLea-Hy: Data compilation from (Tiab and Donaldson, 1996) with a Kozeny-Carman reference line (to be adjustment for site conditions). The shown “actual” value is an example for favourable ISR conditions.
4.3. ISR hydrology

KiLea-Hy has been set up for both wellfield-based ISR (classical form operated from the surface) as well as block leaching (exceptional form operated in underground mine-works or side walls of open pit mines).

4.3.1. Wellfield-based ISR

Figure 18 shows a schematic of wellfield-based ISR (cross section of just one pattern, cf. Figure 9 and Figure 10). For the application the conditions of one pattern have to be multiplied by the number of extractors (patterns) to deduce the conditions for a whole wellfield. Whereas FEFLOW is the hydrological tool for detailed and more reliable simulations, the Thiem equation (2.1) is used in KiLea-Hy to estimate the feasible flow rate per extractor approximately.

![Figure 18: Schematic of wellfield-based ISR (cross section of a wellfield pattern).](image)

The extent of so-called “dead zones” with no or marginal contact of the lixiviant with the ore is increasing at increasing spacing. For KiLea-Hy this effect (shown in Figure 19) has been approximated by an empirical relationship on the basis of FEFLOW simulations.

\[
f(R) = \left[1 + e^{\frac{(R-S_0)}{w}}\right]^{-1}
\]

(4.2)

Where \( R \) is the spacing between extractor and injector, and \( S_0 \) and \( w \) are fitting parameters.
4.3.2. Block leaching

The (in general, percolate) flow through a leach block (Figure 20) is approximated by the Darcy law for generic simulations:

\[ Q = \kappa \cdot A \cdot \Delta H \]  

Where \( \kappa \) is the permeability, \( A \) the area, and \( \Delta H \) the hydraulic head.

Any specific application is simulated by 3D hydrological simulations using FEFLOW, cf. Figure 21.
4.4. ISR leach thermodynamics

The target mineral should be selectively leached from the ore to avoid leaching of harmful components or extensive leaching of gangue minerals. The selection of the appropriate leachant (including oxidant) as well as the adjustment of the acidification and leaching regime is required as they could affect the leaching dynamics and, thus, the extraction of metals (Serederkin et al., 2016).

Leaching of sulfidic deposits requires a sufficient oxidation potential to convert a metal from its insoluble oxidation state (reduced) into its soluble oxidation state (oxidized). The mineral dissolution is a redox half-reaction that releases electrons and can only take place if there are enough electron acceptors (oxidants). As summarized in Table 4, the number of electrons \( n_e \) (in mole) required to leach one mole of a metal ion can be significant, especially for sulfide minerals, which require the oxidation of sulfur (in addition to the oxidation of the metal, if relevant).

For instance, the dissolution of 1 mole chalcopyrite requires 16 moles of electron acceptor (either 16 moles Fe\(^{3+}\) or 4 moles O\(_2\) or equivalent for other oxidants). Based on this fundamental relationship, the maximum concentration \( c_{max} \) of the metal in a PLS can be calculated on the basis of \( n_e \) for given \([A^{e-}]\) (mol/L of electron acceptor). Note that \([A^{e-}] = [Fe^{3+}]\) or \([A^{e-}] = 1/4\cdot[O_2]\), always in mol/L:

\[
(4.4) \quad c_{max} \left[ \frac{g}{L} \right] = \frac{[A^{e-}] \text{[mol]} / n_e}{M \left[ \frac{g}{mol} \right]}
\]

Where \( M \) is the molar mass of the metal considered.

For instance, injecting 5 g/L Fe\(^{3+}\) to dissolve chalcosite \((n_e = 5)\) could result in a maximum Cu concentration in the PLS of 1.14 g/L. The maximum concentration is reduced if other consumers of oxidant are present (e.g. pyrite) or if kinetics is too slow to leach...
this amount of mineral during one (average) pore volume exchange. In other words, the ratio [Ae−]/ne defines a thermodynamic constraint of leaching reduced minerals. The same condition applies to in-situ bioleaching (where O2 at given concentration is consumed by microorganisms to “catalyse” the oxidative leaching (Richter et al., 2018). There is another constraint that applies to in-situ bioleaching: The maximum concentration of dissolved O2 that could be injected into the ore body is given by the solubility of O2 in the leachant as function of temperature and pressure. The relevant effective chemical reaction for the microbially catalysed oxidation of ferrous to ferric iron is:

\[
4Fe^{2+} + O_{2(aq)} + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O
\]

The microbial oxidation effect is indirect, since Fe3+ acts as a direct oxidant to dissolve the reduced metal-bearing mineral. The electron balance (in order to meet the fundamental law of charge conservation) is explicitly considered in KiLea-Hy. The effect of competing oxidant consumers can be taken into account as well (consumption assumed to be proportional to the kinetic rates as an approximation).

Table 4: Number of electrons ne that are released during dissolution of reduced minerals (selection) and need to be compensated by an electron acceptor (oxidant)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Oxidation of metal</th>
<th>Oxidation of S</th>
<th>ne – released electrons per metal ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalcopyrite</td>
<td>CuFeS2</td>
<td>Cu(1)→Cu(2)</td>
<td>2{S(-3/2)→S(6)}</td>
<td>1+2-(15/2) = 16</td>
</tr>
<tr>
<td>Chalcocite</td>
<td>1/2·Cu2S</td>
<td>Cu(1)→Cu(2)</td>
<td>1/2{S(-2)→S(6)}</td>
<td>1+1/2·8 = 5</td>
</tr>
<tr>
<td>Bornite</td>
<td>1/5·Cu5FeS4</td>
<td>Cu(1)→Cu(2)</td>
<td>4/5{S/7/4→S(6)}</td>
<td>1+4/5·(31/4) = 7.2</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>ZnS</td>
<td>S(-2)→S(6)</td>
<td>0+8</td>
<td>8</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS2</td>
<td>2{S(-1)→S(6)}</td>
<td>0+2·7</td>
<td>14</td>
</tr>
<tr>
<td>Uraninite</td>
<td>UO2</td>
<td>U(4)→U(6)</td>
<td>2+0</td>
<td>2</td>
</tr>
<tr>
<td>Coffinite</td>
<td>USiO4</td>
<td>U(4)→U(6)</td>
<td>2+0</td>
<td>2</td>
</tr>
</tbody>
</table>

In the case of acidic leaching the abundance of neutralizing minerals could be critical. Such minerals include:

- Calcareous minerals (like calcite, dolomite in general and others).
- Clay minerals and other silicates (dissolution is significant at very low pH only, since the rate is proportional to \([H^+])^{1/2}\) approximately.
Clay with regard to cation exchange capacity (CEC) as for kaolinite and others, i.e. \( H^+ \) ions are loaded on the adsorptive clay surfaces (mobilizing cations including \( Ca^{2+} \) accordingly).

The neutralizing effect of the above gangue minerals results in a retardation of the acid breakthrough. If Ca is released quantitatively (by calcite dissolution and/or the CEC effect), there is the risk of gypsum precipitation leading to clogging pores in the formation and screens of the extraction wells. The retarded acid breakthrough and the associated effects are shown in Figure 22.

![Figure 22: Dependence of acid breakthrough on calcite content (1D reactive flow)](image)

Obviously, a calcite (or equivalent carbonate) concentration in the order of 1 wt% becomes critical due to the effect on acid consumption (cost factor), the significant \( CO_2 \) release (impact on fluid flow due to 2-phase effects) and the risk of clogging. Calcite concentrations in excess of 2 wt% make acid ISR infeasible.

### 4.5. ISR leach kinetics

A generalized formula of leaching kinetics has already been discussed in Section 2.2.4., Figure 11. For the simulation of acid leach of metals from reduced minerals KiLea-Hy uses the approximate relation

\[
r \approx r_0 \cdot [H^+]^a \cdot [A^{e-}]^b
\]

Whereas the influence of \([H^+]\) is mainly determined by the injection pH, the concentration of the oxidant \([A^{e-}]\) provides the thermodynamic conditions for redox leaching to avoid constraints as discussed in Section 4.4 and to accelerate the leach process, since the parameter \(b\) has always a positive sign. Note that some sulfidic minerals are characterized by \(a<0\) (including chalcopyrite) (Li et al., 2010).
The temperature-dependent Arrhenius factor could be considered easily, if the activation energy $E_a$ is known (cf. Figure 11).

No input data is available for quantifying the Michaelis-Menten term (Figure 11 and Figure 12) to consider the potential effect of microbes (in-situ bioleaching mainly determined by the available $O_2$ dissolved in the leachant).

### 4.6. KiLea-Hy setup

Figure 23 illustrates an example of a KiLea-Hy setup. In the specific case, the following assumptions have been made:

- **Simulation for one 7-spot wellfield pattern of Cu ore (chalcocite with $n_e=5$).**
- **Effective porosity of 25 %, resulting in a permeability of 1.11 m/d and a maximum extraction flow rate of 53.0 m$^3$/h. However, a realistic flow rate of 42.2 m$^3$/h has been considered (80 % of maximum).**
- **11,700 m$^3$ orebody within the wellfield pattern of 5 m thickness. Spacing 30 m.**
- **Cu ore grade 1 wt% at a recovery factor of 95 % (leachable fraction from tests).**
- **ISR amenable metal fraction dependent on porosity**
- **Oxidant concentration equivalent to 5.6 g/L Fe$^{3+}$.**
- **PVE rate of 0.385 d$^{-1}$.**
- **Calcite concentration of 0.1 wt% resulting in an acidification phase of 7 days until breakthrough.**
- **Lixiviant cut-off concentration (shut-down criterion) at 100 ppm.**
- **Interfering minerals neglected (i.e. considering quite favourable leach conditions).**

This wellfield scenario is a quite ideal one; yielding in:

- **Total wellfield lifetime of 516 days at an average Cu concentration of 296 ppm.**
- **Maximum daily production at 0.66 g/L followed by a decline according to leach kinetics until cut-off.**
- **Total Cu recovery: 66. %.**

However, it could be still optimized (e.g. by adjusting the flow rate). The effect of main influencing factors is discussed in the following Chapter 5.
**Figure 23: KiLea-Hy setup as described and corresponding diagrams (as function of both, leach time and PVE).**
5. Key parameters for ISR feasibility

The feasibility of ISR is determined by many factors including general hydrogeology, mineralogy, geochemistry, ore deposit characteristics as well as the overall sedimentary stratification. Once the technical feasibility of ISR is validated, the estimated production rate can be used to determine the economic feasibility.

The following parameters influence the economics of ISR mines (Seredkin et al., 2016):

- Flow rate capacity of the well fields (injection and extraction well capacities).
- Concentration of extracted component(s), i.e. metal of interest in pregnant solutions.
- Overall level of extraction of mined component(s).
- Liquid to solid ratio (LSR) necessary to obtain the desired extraction of the mined component(s). LSR is calculated based on the volume of solutions that passes through the operation block over the entire operation period and on the tonnage of the operational block. A smaller ratio indicates a more economically ideal project.

A more specific and detailed assessment of the economics should consider numerous parameters, such as the (Seredkin et al., 2016):

- Depth of mineralization (drilling and well construction costs).
- Cost of leaching reagents.
- Processing costs, including costs of resin/extractant (IX or SX for metal recovery) and demonstrated processing paths to profitably recover the target metals.
- Existing infrastructure.

This section focuses on the fundamental criteria for the feasibility of underground leaching operations and their influence on the leaching performance (production rate over time). This study is supported by KiLea-Hy simulations.

5.1. Hydrogeological framework

5.1.1. Porosity and permeability

Porosity and permeability are clearly interrelated. The effect on ISR productivity has been simulated for idealized conditions (homogenous ore formation). In general, the leaching solution must be able to move between the injection and extraction wells, in particular, interacting with the metal-bearing mineral quantitatively. Any variability of porosity/permeability in the leaching area can lead to negative effects due to stagnant, non-leaching zones and/or channelling of solutions (Seredkin et al., 2016).
Figure 24 shows the KiLea-Hy results for the (idealized) scenario discussed in Section 4.6, but decreasing the porosity (and the permeability accordingly) from 25 % originally down to 5 % by 5 % increments (assuming 80 % flow rate with reference to the maximum one from Equation (2.1)).

The effect of porosity/permeability on ISR productivity is extremely significant. The observed effects include:

- Strong decrease of flow rate, PVE rate, and production rate.
- The lower porosity/permeability the more retarded the acid breakthrough (clearly seen in the figures).
- At lower porosity, the thermodynamic constraint of PLS grade becomes evident at 1.28 g/L (chalcopyrite limit at 5.6 g/L Fe³⁺).
- Most important, the production rate decreases strongly (as a flow rate effect, but not caused by lower PLS grades).
- The decreasing porosity inhibits the access of ore minerals, thus, lowering the overall recovery significantly.
- The wellfield lifetime increases by lowering the porosity.
- The decrease in porosity for the sequence 25 % / 20 % / 15 % / 10 % / 5 % results in wellfield lifetimes (at 100 ppm cut-off grade) of 1.41 y / 1.99 y / 3.25 y / 8.05 y / > 10 y, respectively.
- The decrease of porosity for the sequence 25 % / 20 % / 15 % / 10 % / 5 % results in total recovery (at 100 ppm cut-off grade) of 66.9 % / 65.3 % / 59.1 % / 49.2 % / x % (far beyond model set-up), respectively.

Figure 24: KiLea-Hy simulations for decreasing porosity (with reference to the case discussed in Section 4.6, performed for 25 %, 20 %, 15 %, 10 % and 5 % porosity (from top to bottom). The permeability decreases as shown for reference curve in Figure 17.
Figure 24 continued.
Summarizing the above results with regard to the feasibility criteria, it can be concluded that ISR becomes technically critical at a porosity of <12% and a permeability of <0.1 m/d. The feasibility window is explicitly shown in Figure 25, also referring to available data for the Rudna mine Cu sandstone which is significantly cemented by calcareous minerals. It shows clearly, that this ore category does not meet the basic feasibility criteria for ISR.

Fracturing of ore that does not meet the ISR criteria could only result in a marginal increase of porosity, but could improve the permeability in a more non-uniform manner (creating fractures or cracks leading to preferential flow). Preferential flow does not improve proportionally the interface between leachant and the mineral of interest.

Figure 25: ISR feasibility window in terms of porosity/permeability (Kozeny-Carman reference as in Figure 17. The blue circle indicates the porosity/permeability range for the Rudna sandstone.
5.1.2. Ore grade, distribution and morphology

In general, it is assumed that ISR can be used for low grade ore deposits, and even in the case of small resources that are unsuitable for conventional mining (Seredkin et al., 2016). Figure 26 shows the effect of ore grade variation, again with reference to the base case shown in Figure 23.

Figure 26: Effect of the ore grade on the resulting recovery curves. Ore grade from top to bottom: 1 wt% Cu (base case shown in Figure 23), 0.5 wt% Cu, and 5 wt% Cu.

Reducing the ore grade from 1 wt% to 0.5 wt% results in a decrease of PLS grade to 50 % accordingly. However, an increase to 5 wt% ore grade shows a clear thermodynamic constraint at 1.28 g/L (if no interfering redox reactions apply). This means the injected oxidant potential is “translated” to the corresponding leachable amount of Cu.
per time unit according to Equation (4.4). If chalcopyrite is considered instead of chal-
cocite the maximum PLS grade would be 0.40 g/L only.

The actual ore grade distribution in 3D could influence (constrain) the recovery, if sig-
nificant heterogeneities apply. This can be simulated by applying 3D reactive transport
models, provided that the ore grade distribution is known.

In addition to the grade, the ore morphology is of relevance to leaching performance.
In an optimum case the well field flow lines fit exactly to the ore body. The better the
fit, the less is the dilution and the higher is the metal concentration in the PLS. This
applies to the horizontal dimension of the ore body and the thickness. In order to opti-
mize the well field properly to the ore morphology, (3D) hydrological models are ap-
plied to optimize:

- The location of wells within the pattern.
- The length and location of the filter section.
- The pump rates (flow rate and pressure balance).

Irregular shapes of the ore body must be followed by the wellfield design (in particular,
by applying non-regular wellfield patterns). This is industrial practice in uranium ISR.

5.1.3. Well field operation parameters

A certain variability of wellfield parameters at given wellfield design is practicable.

First, regarding the depth there is the main effect that drilling and well construction
costs (including power of extraction pump) are strongly correlated to the depth of the
ore body (roughly proportional). The practicable flow rate is given by the hydrological
conditions according to Equation (2.1), i.e. independent on depth, provided that the
pump power is sufficient. The hydraulic head \( S \) (cf. Figure 18) above the extraction
pump is significantly determining the practicable flow rate \( Q \sim S \).

(Seredkin et al., 2016) stated that ISR can be used for low grade ore deposits, deposits
at depths up to 800 m, and even small resources that are unsuitable for conventional
mining. However, it does not apply in general. Favourable conditions for ISR will be
demonstrated on a cost basis in deliverable D7.2, i.e. clearly outlining applicability cri-
teria for a viable operation.

The effect of lowering the flow rate to 50 % is shown in Figure 27. The lower extraction
rate (and PVE rate accordingly) results in a higher maximum PLS concentration. This
is due to the increased contact time between the ore and lixiviant, assuming a sufficient
amount of the oxidant is available as in the example. The production rate is similar in
this case; however, the total wellfield lifetime at 100 ppm cut-off grade is prolonged
from 1.41 y to 1.95 y, whereas the total recovery increases from 66.9 % to 72.7 %.
Only the economic model will provide a conclusive result which scenario is more pro-
ductive. However, the higher PLS grade at reduced flow rate might be favourable for
the metallurgical processing.
The influence of wellfield spacing is very complex. The recovery rates depend on both, PVE rate (much higher due to lower pore volume per given flow rate) and kinetic rates, i.e. also influenced by the oxidant concentration. As rules of thumb it can be summarized:

- Higher-grade ores and lower permeability favour lower spacing.
- Higher spacing reduces the recovery rate due to “dead” zones without contact of leachant to ore body.

The spacing between the injection and extraction wells ranges from 30 to 50 m. At high ore grade and lower permeability a much lower spacing in the order of 15 m might be favourable. Spacing in excess of 60 m has never been reported (too low total recovery). Finally, the economic model linked to the leach model (KiLea-Hy in the present case) is needed to optimize the ISR productivity in dependence on deposit and operational parameters (i.e. it is site-specific).

![Figure 27: Effect of the decreasing the flow rate to 50 %. Simulation as in Figure 23, but at a flow rate of 21.2 m³/h.](image)

5.2. Leaching chemistry

The target mineral should be selectively leachable from the deposit to avoid leaching of harmful components or extensive leaching of rock-forming elements. Selection of the correct leachant and oxidant, as well as calibration of the leaching and acidification
regime, is required as they affect the leaching dynamics and thus the extraction of metals (Seredkin et al., 2016).

The oxidant demand is influenced by both \( n_e \) of the target mineral and the presence of competing redox minerals, whereby competitors increase the overall oxidant consumption. This increases the costs for both the oxidant and the transport of the oxidant to the ore (controlled by the flow rate in dependence on permeability and porosity of the deposit). If competitor concentrations are too high, further costs may ensue due to mineral precipitation and subsequent clogging of pores, screens, and process equipment.

KiLea-Hy has been used to study the leach performance in dependence on oxidant concentration of the leachant. Figure 28 represents the results of simulations at \([A^+]\) of 20, 50, 100, and 200 mmol/L (corresponding to ferric ion concentrations of 1.1, 2.8, 5.6, and 11.2 g/L, respectively) for the standard (reference) case defined in Section 4.6. The corresponding integrative recoveries (at 100 ppm cut-off) are 20.4 %, 55.3%, 66.9 %, and 72.8 %, respectively. The higher the oxidation potential the higher the achievable PLS grade.

The effect of the rate parameter \( r_0 \) in Equation (4.6) is known approximately. In order to demonstrate the influence, the simulations shown in Figure 28 have been repeated for \( r_0 \) increased by a factor of 2. The results are represented in Figure 29.

The increase of \( r_0 \) results in a faster performance at a higher total recovery (in particular, in the case of rather low oxidant concentration). However, the value of \( r_0 \) is one of the main uncertainties. Indeed, \( r_0 \) is not a universal parameter, but depends on the mineral’s micro-structure (texture, inner surface or water-rock interface). In ISR practice, it is common to finally adjust \( r_0 \) to the actual conditions in the wellfield.

Increasing the amount of oxidant in the lixiviant enables higher recoveries in a shorter time. As emphasized above, higher injection concentrations result in higher costs, thus, the optimal balance between the production rate and lixiviant costs must be determined by implementing the economic model (cf. deliverable D7.2).

The dependence on pH is mainly influenced by the parameter \( a \) in the kinetic Equation (4.6). This is an optimizing task influenced by competing reduced minerals.

The presence of competing minerals showing a faster kinetic dissolution rate will influence the dissolution of the mineral of interest. For example, if chalcopyrite should be leached for copper in the presence of pyrite, pyrite will dissolve first (Watling, 2006). Therefore, it should be taken into account to induce the relevant oxidation potential to leach both, pyrite and chalcopyrite.

If the abundances of the main competing minerals (and organics, if relevant) are known, KiLea-Hy is capable to simulate the redox competition explicitly. A rough approach for estimates could be realized by performing the simulation at a lower effective oxidant rate (assuming that a certain fraction is consumed by competitors).
Figure 28: Effect of oxidant concentration on ISR performance – from top to bottom: 20 / 50 / 100 / 200 mmol/L [Ae-]
Figure 29: As for Figure 28, but rate constant $r_0$ doubled.
In summary, KiLea-Hy has been used to demonstrate all major influencing factors in wellfield-based ISR. Note that the software tool has been validated in the uranium ISR industry. Its application to Cu (or any other) ISR is straightforward, however, mainly dependent on the quantification of parameters in the rate Equation (4.6).
6. Block ISR of copper

6.1. Hydrological assessment of Rudna mine test block

6.1.1. Conditions

A fluid flow simulation of the leaching block in Rudna mine was performed by using the finite element software FEFLOW. The modelling is part of WP2 presented in UIT, 2016.

The rock permeability found for the sandstone block in Rudna mine is about 0.1 to 5.2 mD (Klimkowski & Nagy, 2016), i.e. below the feasibility limit (cf. Figure 25). As described in Section 3.1, various methods are available for permeability enhancement, e.g. hydraulic fracturing, acidizing, thermal fracturing and others. Drilling & blasting was performed at Rudna mine to increase the block permeability (in WP3).

Results from the water washing phase of the leach block, started in July 2017, were used as the data basis for the hydrological parameter adjustment (e.g. hydraulic permeability versus porosity). The following conditions characterise the leach block in the Rudna mine:

- Initially the ore was partially saturated (due to discontinuous water tests performed before the continuous water washing phase).
- Percolate flow regime between injection holes and extraction system (drainage).
- Heterogeneous rock.
- Fluid flow through fractured porous media, i.e. based on two categories of porosity (sediment pores and fractures).
- Two-phase system due to unsaturated conditions (water and air).
- Variation of injection conditions (a constant injection pressure is difficult to maintain).

For the simulation of the water washing phase by FEFLOW the following simplifications had to be made (according to input data available):

- Initially dry ore block.
- Homogeneous rock.
- Fractures are not explicitly considered in the model. Observations are reproduced by an averaging parameter set (e.g. for hydraulic conductivity and porosity).
- Constant injection pressure.
Fracturing by blasting requires a compensation volume. 18 holes ($\varnothing = 76$ mm) were drilled for this purpose (cf. Figure 30) in addition to the 11 drill holes ($\varnothing = 60$ mm) that were filled with explosives.

An irregular system of fractures and fissures is expected, with some fractures providing full connectivity between injection and extraction holes and others without full connectivity. The performance of the drilling & blasting has a significant effect on the efficiency of the leaching operation. The risks include:

- Fractures are formed that could cause an unintentional migration of leaching solution (environmental contamination and loss of leaching solution).
- Large fractures may provide the main flow path (preferential flow), inhibiting sufficient leachant contact to the adjacent ore.
- The applicability of Darcy’s Law for the Rudna mine ore block should be looked at critically, according to divergent conditions including:
  - Unsaturated conditions (at least initially) due to dewatering of the underground mine.
- Percolate flow regime between injection holes and extraction hole system (drainage).
- Heterogeneous rock.
- Fluid flow through fractured porous media (double porosity) and two-phase system (water and air).
- Variations in flow conditions (difficult control of injection pressure, in particular, if gypsum precipitation becomes quantitative).

Thus, for data analysis and evaluation, as well as flow and transport process simulation of the block, a suitable theoretical concept and simplified model assumptions are required.

### 6.1.2. Model set-up

The block dimensions are $5 \times 2 \times 10 = 100 \text{ m}^3 (W \times H \times D)$. The block under investigation is located at a distance of 1.8 m below the Cu-shale. As shown in Figure 31, the leach block is embedded into a sandstone environment with at least 2 m distance to the model boundaries. A 2D model approach was found to be sufficient for the purpose of this modelling. Since homogeneous conditions were assumed, the resulting flow profile is symmetric.

The set-up of the block model follows the block design provided by KGHM Cuprum on May 24th, 2016 (see Figure 30). Accordingly, the model considers 11 injection holes and 13 extraction holes, where the latter were arranged in two rows characterized by an offset. The simulations were performed for two different injection pressures: 0.3 and 1.0 bar, that were found as lower and upper values during the water washing phase. The injection pressure is applied to each injection hole.

![Figure 31: Set-up of 2D block model (FEFLOW)](image)
Figure 31 further presents the dimensioning and parameter specifications for the 2D block model (FEFLOW). A low initial saturation was assumed ($S_{ini} = 0.0025$), representing very dry conditions of the dewatered underground. Richard’s equation was applied for the unsaturated flow calculation. The van Genuchten parametric model was used for the calculation of the relative hydraulic conductivity (related to the saturation). The hydraulic conductivity and porosity of the sandstone block result from model calibration described below. The values should represent block conditions after blasting. For the surrounding sandstone and the overlying shale, hydraulic conductivities and porosities follow measured data presented by (Klimkowski & Nagy, 2016). A summary of initial conditions and boundary conditions is given in Table 5.

Table 5: Summary of model setup of the 2D block (FEFLOW)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsaturated flow equation, transient fluid flow, van Genuchten model</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Domain and mesh:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width; height</td>
<td>9; 7</td>
<td>m</td>
</tr>
<tr>
<td>Number of dimensions</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>Element type</td>
<td>triangle</td>
<td>–</td>
</tr>
<tr>
<td>Mesh elements / nodes</td>
<td>4,350 / 2,226</td>
<td>–</td>
</tr>
<tr>
<td><strong>Material Properties – Fluid Flow:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic conductivity $K_x$</td>
<td>see Figure 31</td>
<td>m·d⁻¹</td>
</tr>
<tr>
<td>Anisotropy settings $K_z/K_x$</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Specific storage</td>
<td>$1.0 \cdot 10^{-4}$</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>Initial saturation</td>
<td>0.0025</td>
<td>–</td>
</tr>
<tr>
<td>Porosity (block / undisturbed sandstone / shale)</td>
<td>0.05 / 0.002 / 0.001</td>
<td>–</td>
</tr>
<tr>
<td><strong>Fluid Flow Boundary Condition:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic-head (pressure)</td>
<td>0.3 – 1.0</td>
<td>bar</td>
</tr>
<tr>
<td><strong>FEM:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial time step size</td>
<td>$1.0 \cdot 10^{-4}$</td>
<td>d</td>
</tr>
<tr>
<td>Simulation time period</td>
<td>61</td>
<td>d</td>
</tr>
</tbody>
</table>
6.1.3. Model Calibration

Model calibration was performed by varying the hydraulic conductivity and porosity of the leach block until a good fit between observed and simulated injected water volume is achieved. The operation update of the pilot plant, summarised by Hatch (2017), provides the data basis (total injected volume) for the model calibration. The progress report describes the first phase of the pilot plant testing, where water was injected into the block to wash out Cl (also referred to as water washing phase).

As shown in Figure 32, a total of 72 m³ of water was injected into the block in the period from 2017/07/11 to 2017/09/09 (Hatch, 2017). Thus, an average flow rate of 1.2 m³/d was derived for the complete injection period (61 days).

![Figure 32: Cumulative injected water volume (L) during the wash phase (Hatch, 2017)](image)

A good agreement of simulated and observed injection volumes could be achieved for a porosity of $\varepsilon = 0.05$ and a hydraulic conductivity of $K = 0.01$ m/d and $0.0035$ m/d for $p_{\text{inj}} = 0.3$ bar and 1 bar, respectively (cf. Table 6).

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Hydraulic conductivity (m/d)</th>
<th>Porosity (-)</th>
<th>Total volume injected (m³)</th>
<th>Simulated</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.01</td>
<td>0.05</td>
<td>72.3</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0035</td>
<td>0.05</td>
<td>75.0</td>
<td>72</td>
<td></td>
</tr>
</tbody>
</table>
6.1.4. Model Results

Figure 33 and Figure 34 show the percolation of water (similar for lixiviant) through the leaching block as function of time. The dashed outline depicts the position of the block. Injection holes are indicated by yellow markers and extraction holes are highlighted by white markers.

After about 3 days, a full saturation of the block was observed for the two different injection pressures and hydraulic conductivities as derived during model calibration. In both injection pressures scenario, the surrounding area of the block gets fully saturated over the simulated time period due to the very low porosities of the (fractured) sandstone block.

From the two simulations of the block saturation the following was observed (also meeting the expectations):

- The lower the injection pressures the less solution spreads into the surrounding formations of the block.
- The higher the hydraulic conductivity $K$ the faster solution percolates through the block.

$p_{inj} = 0.3$ bar

Figure 33: Saturation of the block over time ($t = 0.5, 1, 3, 5, 10$ and $61$ days) at an injection pressure $p_{inj} = 0.3$ bar (dashed outline indicates block).
In order to develop a further understanding of the pilot plant test results, observed and simulated pressure data were compared. The pilot plant observation system provides continuous measurement data of conductivity, temperature and pressure at different observation points. According to the pressure observation points (a-e) in the leach block, observation points were defined within the leach block model Figure 35.

Figure 34: Saturation of the block over time (t = 0.5, 1, 3, 5, 10 and 61 days) at an injection pressure $p_{\text{inj}} = 1$ bar (dashed outline indicates block).

Figure 35: Model observation points positioned according to the pilot plant monitoring system
From the comparison of measured and modelled pressure values (Figure 36) it can be concluded:

- Evident increase of pressure at sensor c indicates saturation.
- A constant, very low pressure (~1-2 mbar) at sensor a leads to the conclusion that water bypasses that area and no flow is apparent (alternatively, the possibility of a blocking of the pipe should be assumed).
- Pressure at sensor d increases at the end of the observation period after approximately 55 days of injection.
- Pressures at sensors b and e show fluctuations over time, especially for sensor e partial saturation and subsequent dewatering was observed.

When comparing the observed and simulated pressure distributions at the different observation points over time, some deviations become apparent. Due to the relatively fast saturation of the block in the simulation, a constant pressure is achieved quickly at holes a and d (red and blue curves) and short time later pressures at holes b, c and e decrease (green, yellow and grey curve) to a constant value (Figure 36, lower image). The resulting pressures correspond to the respective height of the observation points. Moreover, simulated maximum pressures are lower than observed ones (e.g.
for sensor c). The differences result from the modelling approach, where homogenous rock conditions and an average hydraulic conductivity were assumed instead of a fractured rock model.

In summary, the simulation of the water washing phase of the pilot plant operation improved the understanding of the flow conditions in the block after drilling & blasting had been performed. A homogeneous effective hydraulic conductivity $K$ and porosity $\varepsilon$ were assumed in order to represent the overall flow conditions (in contrast to the obvious heterogeneity of the test block). This simplification is considered to be feasible, in particular, in view of the lack of knowledge of the detailed block conditions after blasting. Nevertheless, it needs to be taken into account that real-site conditions could differ due to the occurrence of fractures of variable size and shape.

The simulation of the two different injection pressures revealed $K = 0.01 \text{ m/d}$ for 0.3 bar and $K = 0.0035 \text{ m/d}$ for 1 bar. Compared to the initially measured $K$ values of the sandstone (about 0.002 m/d) the simulated effective $K$ values are slightly higher. This quantifies the (moderate) flow enhancement by drilling & blasting.

6.2. Block ISR model and KiLea-Hy

Using exactly the same kinetic parameters as for the simulations of wellfield-based ISR in Chapter 5, KiLea-Hy has been applied to block leaching scenarios to predict and reproduce the Rudna mine trial. The basic input setup and results of the first simulation (without any parameter adjustments) are represented on Figure 37.

The setup is in accordance to the block data described above:

- Leach block dimensions: $10 \times 5 \times 2 \text{ m}^3$ (L x W x H).
- Assumed porosity of 6 % results in an estimated permeability of 0.01 m/d, considering conditions after drilling & blasting (cf. Figure 25 and Section 6.1).
- The concentration of ferric Fe$^{3+}$ was assumed to be 3 g/L, i.e. $[A^e_] = 54 \text{ mM}$.

The simulation demonstrates the following:

- The resulting flow rate is $0.041 \text{ m}^3/\text{h} = 1.0 \text{ m}^3/\text{d}$, i.e. reproducing the block leach conditions in the Rudna mine quite well.
- Assuming an average calcite concentration of 0.5 wt%, the duration of the acidification phase at an injection pH of 1.2 is 110 days. Both injection pH and calcite concentration in the sandstone determine the acid breakthrough. Preferential flow conditions in the fractured rock influence the observed pH breakthrough remarkably.
- The leaching under such conditions turns out to be thermodynamically constrained, i.e. Equation (4.4) applies.
- Since the simulation has been performed for $n_e = 5$ and without considering any competing redox reactions, the resulting (constrained) PLS grade of 0.69 g/L
Cu is an upper limit. The estimated uncertainty range is about 0.2 to 0.6 g/L Cu in the PLS.

- The estimated recovery is in the order of 25% after 1000 days, only.
- The (maximum) daily production rate is estimated to 0.68 kg/d.

**Figure 37: Block ISR simulation for the Rudna mine trial.**
The simulations additionally verified that the application of oxidative leaching to the Cu-bearing dolomite and shale strata in the Rudna deposit is not feasible, mainly due to even higher calcareous abundances and unfavourable permeability conditions.

6.3. Summary

Both, hydrological and chemical conditions observed in the Rudna test block were investigated in detail. The models (FEFLOW and KiLea-Hy, respectively) reproduce the observed trends quite well despite the approximation of a homogeneous rock.

In the BIOMOre leaching trial, the regeneration of oxidising potential of the leaching solution is achieved by ex-situ biooxidation. The main reaction is the oxidation of Fe$^{2+}$ to Fe$^{3+}$. The economic assessment (WP7.2) has to demonstrate if this option is more viable than a purely chemical oxidation.

The simulations verified in agreement with the experiences of the pilot test that the conditions of the sandstone in the Rudna deposit are unfavourable for an ISR operation, in particular, for the special case of block leaching. The main constraints include the high abundance of calcareous minerals, the high demand for oxidant and the unfavourable permeability conditions.

The permeability enhancement by drilling & blasting was successful, but did not change the overall picture significantly.

The application of oxidative leaching to the Cu-bearing dolomite and shale strata in the Rudna deposit is not feasible due to even more unfavourable conditions than in the sandstone layer.
7. Conclusions

For the assessment of ISR operations for oxidative Cu leaching including optional permeability stimulation and biooxidation (the BIOMOre process) feasibility criteria have been generalized:

- The hydrogeological criteria (porosity, permeability, and confinement predominantly) together with the orebody morphology (including ore grade distribution) define the achievable volumetric flow and, hence, the determining pore volume exchange (PVE) rate.

- The mineralogical/geochemical, groundwater-chemical and microbial criteria define the leaching kinetics, usually expressed by absolute kinetic rates as function of chemical and optionally microbial parameters. Pre-conditioning could improve/expedite the recovery for a more economic operation.

- Both, flow rate of leaching solution and metal grade in the pregnant leach solution (PLS) determine the production rate as the basis for the economic assessment of the ISR technology.

The applicability of permeability stimulation technologies depends on geomechanical deposit characteristics. If the conditions are favourable, wellfield stimulation by fracturing could enhance the permeability for increasing recovery by creating cracks/fractures and connect isolated pores to contribute to the fluid flow.

The ex-situ bio-oxidation of Fe in an aerated bioreactor is part of the BIOMOre process. The indirect catalysis of leaching by microbial (re-)oxidation of Fe$^{2+}$ to Fe$^{3+}$ as directly acting e$^{-}$ acceptor is a well verified mechanism. The economic advantage of biooxidation compared to purely chemical oxidation mainly depends on the retention time of the biooxidation process (cf. deliverable D7.2).

The chemical key parameters for (bio-)leaching productivity rely on reactive transport simulations of ISR from sulfidic Cu ores based on kinetic rates as function of pH and oxidation potential (concentration of e$^{-}$ acceptors) in comparison with thermodynamically driven metal dissolution (constrained by oxidation potential).

Based on the feasibility criteria, a generic kinetic leach model (KiLea-Hy) was developed that simulates the production rates (flow rate x metal concentration) during the lifetime of an ISR operation for (i) the (standard) wellfield operation and (ii) the specific block leaching in underground mineworks.

A comprehensive parameter study quantified the most critical parameters affecting the production rate of a wellfield operation:

- Porosity/permeability
- Oxidant concentration
- Competing minerals consuming reactants and constraining the leaching rate of the metal of interest:
- Neutralizing minerals (e.g. calcareous minerals consuming sulfuric acid),
- Reduced minerals (e.g. pyrite) consuming oxidation potential and organics undergoing oxidative degradation under acidic conditions.

- Wellfield design (hydrological) and wellfield performance (chemical)

The software KiLea-Hy is suitable to reproduce the block leaching test results obtained from the Rudna mine test and, most important, to convert the test results into the recovery functions for the corresponding wellfield ISR case consistently.

The assessment of the Rudna mine block leach trial showed that the existing conditions in the Cu-bearing dolomite, shale, and sandstone strata are unfavourable for the BIOMOre process.

Finally, KiLea-Hy is applicable to optimize any ISR operation with regard to PVE (within hydrological limits) and leaching chemistry. The quantification of the productivity of ISR in dependence on both, realized flow rate and leaching rate, finally determining the production rate provides the input for the economic assessment. It is combined with the (in general, hydrometallurgical) processing to separate the metal of interest from the PLS, in each case followed by eletrowinning EW or alternative separation/refining technologies. The combination with the economic model is demonstrated in deliverable D7.2.
8. References


[In the style of (ref. IAEA ISL), reworked and extended.]

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition, explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer</td>
<td>A permeable underground sediment or rock formation capable of storing and allowing the flow of water (groundwater).</td>
</tr>
<tr>
<td>Aquitard</td>
<td>A low-permeability underground sediment or rock formation that retards but may not entirely prevent the flow of water (groundwater).</td>
</tr>
<tr>
<td>Baseline</td>
<td>Data acquired to identify the state of the environment prior to any disturbance from mining. It should give a pre-mining inventory of factors such as the diversity and abundance of flora and fauna, agricultural or pastoral activities and productivity, and quality of air and water, particularly groundwater. The values acquired can be used as a benchmark for final mine rehabilitation. Social baseline data is also relevant to most projects.</td>
</tr>
<tr>
<td>Bleed</td>
<td>In most but not necessarily all ISL operations, ‘bleed’ is a slight excess of pumped water compared to injected water is maintained, which may vary from &lt;1% to a few % of the water extracted. This helps maintain mining solutions within the planned mined areas, but also generates excess water that must be used or disposed of.</td>
</tr>
<tr>
<td>Block Leaching</td>
<td>The leaching of a block of ore accessed by a conventional underground mine, where mining solution is passed through a block of blasted ore and recovered. Whilst this has similarities to ISL mining as described here, it is not included except by passing reference.</td>
</tr>
<tr>
<td>Confinement</td>
<td>(In ISR) The (vertical) hydraulic separation of the (intended) ISR mining zone (wellfield) in an aquifer by adjacent aquitards. In general, it requires the absence of unwanted (hydraulic) connectivity, e.g. by tectonic faults.</td>
</tr>
<tr>
<td>Cut-off grade</td>
<td>Metal concentration in the lixiviant of a depleting wellfield, at which the ISR operation becomes uneconomic. Shutdown criterion, usually applied to individual extraction wells.</td>
</tr>
<tr>
<td>Effluent</td>
<td>Wastewater from chemical/metallurgical processing</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>EIA/EIS</strong></td>
<td>Environmental Impact Assessment/Statement, an assessment or statement of the environmental impacts of a project, usually incorporating some form of risk assessment and measures proposed to minimize identified, expected or possible negative impacts. May include a social impact assessment.</td>
</tr>
<tr>
<td><strong>Elution</strong></td>
<td>IX process. Recovery of uranium (in form of anionic uranyl complexes) from the loaded resin beads by a highly ionic eluant stream (containing nitrate, chloride or others), thus, forming a pregnant eluate with a high uranium concentration for further processing. To be followed by a resin regeneration (also referred to as conversion) for reuse in the sorption circuit (c.f. sorption).</td>
</tr>
<tr>
<td><strong>Excursion</strong></td>
<td>Movement of mining or waste solution beyond the area intended/permitted.</td>
</tr>
<tr>
<td><strong>Extraction well</strong></td>
<td>A cased well with a filter section through which mining solution is removed from the orebody being mined by pumping.</td>
</tr>
<tr>
<td><strong>GT</strong></td>
<td>Grade x Thickness (of an orebody) in wt%·m, to be distinguished from Productivity.</td>
</tr>
<tr>
<td><strong>Hydraulic conductivity (permeability)</strong></td>
<td>The inherent ability of porous rock to transmit fluid (c.f. transmissivity).</td>
</tr>
<tr>
<td><strong>Injection well</strong></td>
<td>A cased well with filter section through which mining solution is introduced to the orebody being mined, either pumped or under gravity. The mining solution is removed via an extraction (or recovery) well.</td>
</tr>
<tr>
<td><strong>ISL/ISR</strong></td>
<td>In-situ leaching / In-situ recovery, a form of solution mining where mining solution is circulated underground through a sedimentary, saturated ore body to dissolve and bring the target material to the surface for further recovery.</td>
</tr>
<tr>
<td><strong>IX (Ion Exchange)</strong></td>
<td>Transfer (absorption/desorption) of ions between a solution and ion exchange sites on surfaces (on and inside porous IX resin beads in uranium recovery applications). Together with SX, a predominant technology to recover a metal from loaded mining solutions in ISL applications (cf. sorption and elution).</td>
</tr>
<tr>
<td><strong>Mining Solution</strong></td>
<td>Usually local groundwater that is chemically modified to cause it to dissolve the target mineral (uranium) when it is caused to move through an orebody by pumping. To date mining solutions for uranium ISL are either alkaline (carbonatic) or acidic (sulfuric), usually with the further addition of an oxidizing agent such as gaseous oxygen or hydrogen peroxide.</td>
</tr>
<tr>
<td><strong>Observation well also called monitoring well</strong></td>
<td>A well installed in, above, below or laterally to the orebody being mined to allow water level measurement and/or groundwater sampling. This allows the hydrogeology to be understood and specifically identify possible movement of mining solution beyond the mining area, or to identify potential impacts on identified users or receivers of groundwater in the vicinity of an operation.</td>
</tr>
<tr>
<td><strong>Ore</strong></td>
<td>An occurrence of a mineral in quantity and quality that could be mined. Note that there may be official, more detailed definitions in some jurisdictions.</td>
</tr>
</tbody>
</table>
| **Porosity** | Measure of the void space fraction in a soil/rock material. \[ \text{Porosity} \, \varepsilon = \frac{V_V}{V_T} \]  

\( V_V \) – void volume. \( V_T \) – total volume. 

\( V_V \) filled with (ground) water and or air (saturated to vadose conditions). 

\( V_V \) is usually diversified into free-fluid pore volume (connected pores contributing to the fluid flow) and stagnant pores (not connected or too small pores not contributing to the fluid flow). |
### Pattern (well pattern)
Refers to the design of the locations of injection and extraction wells relative to each other. ‘A pattern’ may refer to a single extraction well and the injection well(s) that serve it.

### PER
Public Environment(al) Report, typically a smaller form of an Environmental Impact Statement, or a report of environmental performance of a project released publically.

### Pore Volume Exchange (PVE)
(Average) replacement of the mining solution in the total pore volume of a wellfield or a wellfield pattern by the injected lixiviant. The PVE rate is given by $Q/V_P$.

- $Q$ – Volumetric flow rate of lixiviant.
- $V_P$ – (Effective free-fluid) Pore volume per wellfield or wellfield pattern.

The (average) time required for a PVE is the inverse of the PVE rate.

### Productivity
Mass of metal (of interest) per area [kg/m²], usually defined for distinguished ore horizons. Related to GT: Productivity $P$ [kg/m²] = GT [wt%·m] · $\rho_{ore}/100\%$.

- $\rho_{ore}$ – density/specific gravity of ore [in t/m³ = 1,000 kg/m³].

### Refortification
Chemical conditioning (i.e. controlled dosage of chemicals) of the barren lixiviant before injection (into ISR wellfields).

### Sorption
IX process. Adsorption of uranium (in form of anionic uranyl complexes) from the loaded mining solution to resin beads in an ion exchange column as part of the recovery process (c.f. elution).

### Transmissivity
The ability of porous rock to transmit fluid, generally applied to a layer of rock of a certain thickness (c.f. hydraulic conductivity/permeability).

### SX (Solvent Extraction)
Separation process in which a water-based and an organic-based solvent are brought into contact to selectively extract a component (metal species) from the leaching solution (PLS).

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